

# Provision of LCI data in the European aluminium industry Methods and examples

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## Abstract

**Background, aim, and scope** The development of robust and up-to-date generic life cycle inventory data for materials is absolutely crucial for the LCA community since many LCA studies rely on these generic data about materials. LCA databases and software usually include within their package such generic LCI datasets. However, in many cases, the quality of these data is poor while the methodology and the models used for their development are rarely accessible or transparent. This paper presents the development of robust European LCI datasets for the production of primary and recycled aluminium ingots and for the transformation of aluminium ingot into semi-finished products, i.e. sheet, foil and extrusion.

**Materials and methods** The environmental data have been collected through an extensive environmental survey, organised among the European aluminium industry, focusing on the year 2005 and covering EU27 countries as well as EFTA countries (Norway, Iceland and Switzerland). From this survey, European averages, i.e. foreground data, have been calculated for the direct inputs and outputs of the various aluminium processes. Using the GaBi software, the foreground data have been combined within LCI models integrating background LCI data on energy supply systems, ancillary processes and materials. For the primary aluminium production (smelters), a specific model for the electricity production has been developed. The methodol-

ogy for the data consolidation and for the development of the various models is explained as well as the main differences between the new modelling approach and LCI models used in the past. An independent expert has critically reviewed the entire LCI project including data collection, models development, calculation of LCI data and associated environmental indicators.

**Results** As confirmed by the critical review, the new LCI datasets for aluminium ingot production and transformation into semi-finished products have been developed through a robust methodology in full accordance with ISO 14040 and 14044. Most significant environmental data and LCI results are reported in this paper with an emphasis on energy use and the major emissions to air. The full environmental report, including the critical review report and the calculation of environmental indicators for a pre-set of impact categories, is available on the website of the European Aluminium Association (EAA 2008). Whenever possible, the updated European averages and the new LCI data are compared with previous results developed from two past European surveys covering respectively the years 2002 and 1998. For the aluminium processes related to primary production, European averages are also benchmarked against global averages calculated from two worldwide surveys covering the years 2000 and 2005.

**Discussion** While some data evolutions are directly attributed to the variation of foreground data, e.g. raw materials consumption or energy use within the aluminium processes, modifications related to the system boundaries, the background data and the modelling hypotheses can also influence significantly the LCI results. For primary aluminium production, the evolution of the foreground data is dominated by the strong decrease of PFC (perfluorocarbon) emissions (about 70% since 1998). In addition, the electricity structure calculated from the refined electricity

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model shows significant differences compared to previous models. In the 2005 electricity model, the hydropower share reaches 58% while coal contributes to 15% only of the electricity production. In 1998, the respective share of coal-based and hydro-electricity were respectively calculated to 25% and 52%. As a result, the electricity background LCI data are then significantly affected and influence also positively the environmental profile of primary aluminium in Europe. For the semi-production processes, the reduction of process scrap production, especially for extrusion and foil, demonstrates the increase of process efficiency from 1998. In parallel, a significant reduction of energy use is observed between 1998 and 2005. However, this positive trend is not fully reflected within LCI data due to the significant contribution of the background electricity data. The choice of the electricity model plays also a critical role for these transformation processes since electricity production contributes to about 2/3 of the consumption of the non-renewable energy and to about the same level of the air emissions. In such a case, the move from the UCPTTE electricity model used in the past towards the EU25 electricity model used for the development of the updated LCI data has a detrimental effect on the environmental profile of the three LCI datasets respectively related to sheet, foil and extrusion. In addition to energy and process scrap reduction, the reduction of the VOC (volatile organic compounds) emission is also a major trend in foil production. Finally, for old aluminium scrap recycling, the new LCI data show a dramatic improvement regarding energy efficiency, reinforcing the environmental soundness of promoting and supporting aluminium recycling within the aluminium product life cycles.

**Conclusions** This paper shows the development of generic LCI data about aluminium production and transformation processes which are based on robust data, methodologies and models in full accordance with ISO 14040 and 14044 standards, as confirmed by the critical review. The publishing of these LCI datasets definitely shows the commitment of the European aluminium industry to contribute in a transparent, fair and scientifically sound manner to product sustainability in a life cycle thinking perspective.

**Recommendations and perspectives** Software houses and LCA practitioners are invited to update their generic European data on aluminium with the herewith datasets. Even if the quality and the completeness of these LCI data reach a high standard, some areas for data improvements have been identified, as described within the review report. Land use, water use and solid waste treatment appear as three priority areas for data refining and improvement. The land use dimension, particularly meaningful for bauxite mining, is not covered in the current LCI data while it is now integrated within many LCA studies. Up to now, the

reporting of meaningful and robust data on water origins and use have not been possible due to the huge discrepancies between the surveyed sites combined with the difficulty to report coherent input and output water mass flows. The development of water data, only focussing on water-stressed areas, will most probably make more sense in the future. Finally, collecting more qualitative information about solid waste processing and treatment will help to include such operations within the system boundaries and to model their associated air, water and soil emissions.

**Keywords** Aluminium · Europe · Extrusion · Foil · Generic LCI data · Primary production · Recycling · Sheet

## 1 Background, aim and scope

The European aluminium industry promotes life cycle thinking and supports the use of LCA which contributes to further environmental improvements in aluminium product development in a life cycle concept. In this context, the European Aluminium Association (EAA) has published several environmental profile reports which contain life cycle inventory (LCI) data for the aluminium production and transformation processes in Europe (EAA 1996, 2000). In 2006, the European Aluminium Industry decided to update these LCI datasets and the European Aluminium Association (EAA) organised an extensive environmental survey referring to the year 2005. From this environmental survey, updated LCI datasets have been calculated and published in April 2008 in a new environmental profile report (EAA 2008) available for download from the EAA website. This new environmental report provides up-to-date life cycle inventory data (LCI) for aluminium production and transformation processes in Europe. The report and the associated LCI data have been developed in full reference to the two relevant ISO standards 14040 and 14044. As an independent expert, Walter Klöpffer has reviewed the full LCI project from process input and output data collection and consolidation up to the development of the generic LCI models and the calculation of the associated datasets. Walter Klöpffer details his reviewing experience in a separate paper included in this special edition (Klöpffer, 2009).

This paper highlights the methodology used to develop these updated LCI datasets. This description includes not only the data collection, consolidation and averaging, i.e. the calculation of the foreground data, but also all the LCI data modelling aspects. ‘Gate to gate’ data, i.e. direct inputs and outputs at process level, as well as LCI data are compared to previous European data. For primary production, European data are also benchmarked against global figures. Complete datasets are available on request at

lci@eaa.be. This paper focuses on the most relevant inputs and outputs with a special focus on energy use and air emissions.

## 2 The aluminium product life cycle

The typical life cycle of an aluminium product system is reported in Fig. 1.

The main raw material for aluminium is bauxite, which is extracted from bauxite mines and processed into aluminium oxide at alumina plants. Aluminium metal is produced from aluminium oxide by an electrolytic process at plants typically called smelters. In addition to alumina, the main raw materials are carbon anodes and aluminium fluoride. Aluminium from the smelters is alloyed and cast into ingots for rolling, extrusion or product casting. Aluminium primary production includes all these processes from bauxite mining up to ingot casting.

Rolling and extrusion are the two major processes used to transform aluminium ingots into semi-finished products, e.g. sheet foil and profile. These three types of semi-

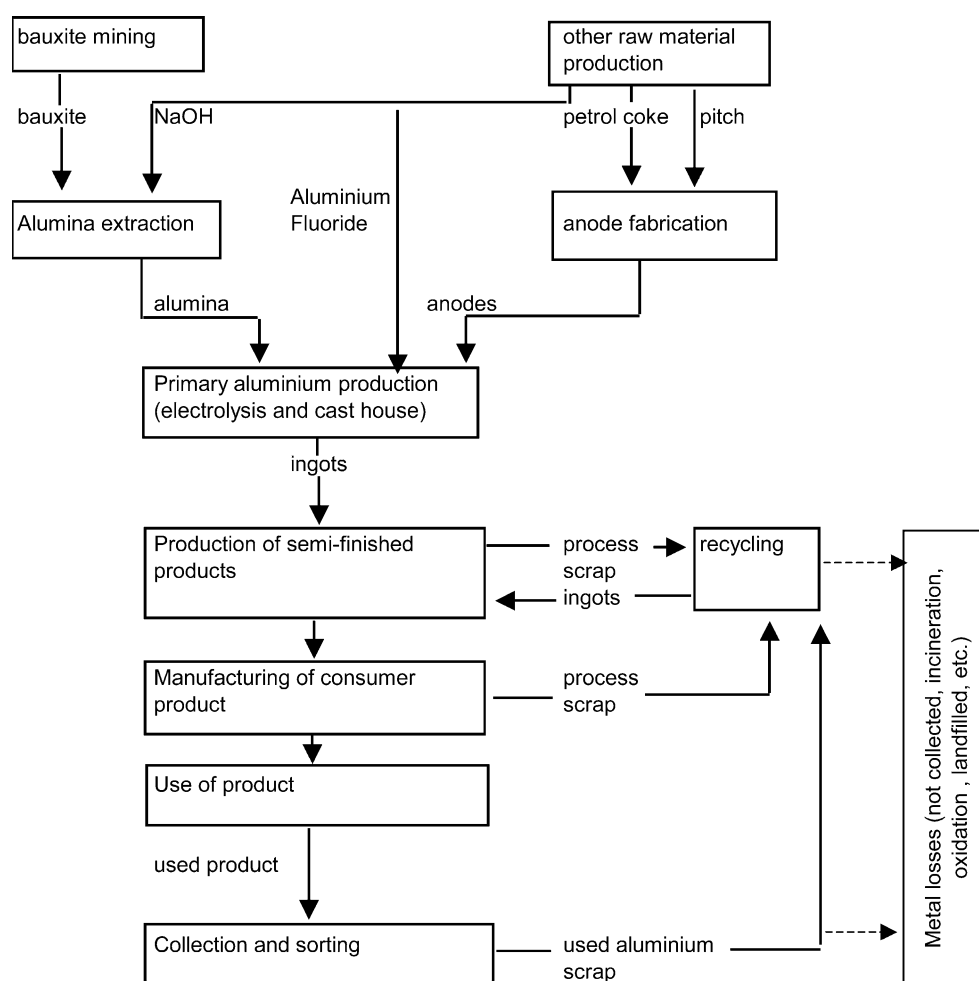
finished products are covered in this LCI study while aluminium plate and aluminium cast products have not been covered.

The aluminium semi-finished products are usually used to manufacture components like aluminium window frames, bicycle frames or car body parts which are then integrated into consumer products like cars or aluminium windows. These manufacturing operations as well as the use phase of the consumer product are not covered within this LCI project.

The fabrication of semi-finished aluminium products as well as the manufacturing of consumer products generate aluminium scrap called new or process scrap. These scrap are collected and recycled through the so-called remelters (EAA 2004). Aluminium scrap from products after their service life, called used, old or post-consumer aluminium scrap, are also usually recovered for recycling by the so-called refiners. The process scrap recycling (remelting model) and the old aluminium scrap recycling (refining model) will be both addressed in this LCI project.

The next section describes in more detail the aluminium processes which are covered within this LCI project.

**Fig. 1** Typical flow chart of the life cycle of an aluminium product



### 3 The aluminium processes (Kammer 1999)

#### 3.1 Primary aluminium production

The main raw material for aluminium is bauxite, which is extracted from bauxite mines, mainly by open-cast mining. Bauxite is composed primarily of one or more aluminium hydroxide compounds, plus silica, iron and titanium oxides as the main impurities. More than 150 million tonnes of bauxite are mined each year. The major locations of deposits are found in a wide belt around the equator.

Bauxite has to be processed into pure aluminium oxide (alumina) before it can be converted to aluminium by electrolysis. This is achieved through the use of the Bayer chemical process in alumina refineries. The aluminium oxide contained in bauxite is selectively leached from the other substances in an alkaline solution within a digester. Caustic soda and lime are the main reactants in this leaching process which takes place in autoclaves at temperature between 100 and 350°C (depending on alumina reactivity). The solution is then filtered to remove all insoluble particles which constitute the so-called red mud. On cooling, the aluminium hydroxide is then precipitated from the soda solution, washed and dried while the soda solution is recycled. The aluminium hydroxide is then calcined, usually in fluidised-bed furnaces, at about 1,100°C. The end-product, i.e. aluminium oxide ( $\text{Al}_2\text{O}_3$ ), is a fine-grained white powder.

Primary aluminium is produced in electrolysis plants (frequently called ‘smelters’), where the pure alumina is reduced into aluminium metal by the Hall–Héroult process. Between 1,920 and 1,925 kg of alumina is needed to produce 1 tonne of aluminium. The reduction of alumina into liquid aluminium is operated at around 950°C in a fluorinated bath (i.e. cryolite) under high intensity electric current. This process takes place in electrolytic cells, where carbon cathodes form the bottom of the pot and act as the negative electrode. Carbon anodes (positive electrodes) are held at the top of the pot and are consumed during the process when they react with the oxygen coming from the alumina. There are two major types of cell technology in use. All potlines built in Europe since the early 1970s use the pre-bake anode technology, where the anodes, manufactured from a mixture of petroleum coke and coal tar pitch (acting as a binder), are ‘pre-baked’ in separate anode plants. In the Söderberg technology, the carbonaceous mixture is fed directly into the top part of the pot, where ‘self-baking’ anodes are produced using the heat released by the electrolytic process. In 2005, the European production mix was 90% of pre-bake technology for 10% of Söderberg technology. The electrical energy required for the electrolysis, comprised between 13,000 and 18,000 kWh/tonne of aluminium, constitutes

the major part of energy consumption in aluminium primary production. Therefore, the generation of this electricity has been specifically modelled.

At regular intervals, molten aluminium tapped from the pots is transported to the cast house where it is alloyed in holding furnaces by the addition of other metals and aluminium scrap. The melt is then cleaned of oxides and gases before casted into ingots. Cast houses produce a wide variety of products and alloys. Since it is not possible to produce one dataset for every type of product and alloy, average data have been developed for a generic aluminium ingot covering ingot for rolling (slabs), for extrusion (billets) or for remelting. Rolling ingots, also called slabs (rectangular shape), and extrusion ingots, also called logs or billets (cylindrical shape), are produced through direct chill (DC) casting technology consisting in pouring liquid metal into short moulds on a moving platform which is lowered into a water-filled pit. Before exiting the cast house, the ends of the rolling ingots and extrusion ingots are usually sawed and directly recycled into the holding furnace. The products exiting the cast house are usually sawn rolling ingots, sawn extrusion ingots or ingots for remelting.

#### 3.2 Semi-finished products fabrication

*Sheet* The starting stock for sheet production is the DC (direct chill semi-continuous cast) ingot. The size of the ingot depends on the size of the DC unit available, the hot rolling mill capacity, volume required for a particular end use and to some extent the alloys being cast. Ingots up to over 32 tonnes in weight, 500–600 mm thick, 2,000 mm wide and 9,000 mm long are produced. Before rolling operations, the rolling ingot is machined to cut the ends (sawing) and to even the surfaces (scalping).

According to alloy grade, a thermal treatment of homogenisation needs to be applied to the aluminium ingot before any transformation. The applied homogenisation temperature, usually comprised between 450 and 550°C, depends on the alloy type while the duration, usually comprised between 15' and several hours, depends on the thickness of the ingot. Before hot rolling, the ingot needs to be pre-heated to around 450–500°C prior to successive passes through a hot rolling mill where it is reduced in thickness to about 4–6 mm. Nowadays, ingot homogenisation and pre-heating are usually combined in order to reduce the energy consumption. The strip from the hot rolling mill is coiled and stored before cold rolling which is usually done in the same site. Cold mills, in a wide range of types and sizes, are available; some are single stand, others three stands and some five stands. Final thickness of the cold rolled strip or sheet is usually comprised between 0.2 and 2 mm.

Finishing operations include:

- Sizing, e.g. trimming, slitting and blanking
- Annealing according to alloy grades
- Final surface preparation (excluding coating and/or painting)

Main uses of aluminium sheet products are in transport and building applications as well as in packaging applications as intermediate products, i.e. mainly can stock and foil stock.

**Foil** Similarly to the sheet production, the classical production route for foil production uses an aluminium rolling ingot (slab) as starting material for the production of rolled aluminium foil, which is first rolled into foil stock, i.e. the specific input for foil fabrication. In addition to the classical production route, foil stock can also be produced directly through the strip casting process consisting in casting the molten aluminium directly into a strip which is directly hot rolled. In the LCI dataset on foil, a ratio of 80% classical route and 20% strip casting route for the foil stock production was used. Foil stock is usually annealed before further processing.

Foil fabrication is carried out by cold rolling from foil stock with a thickness of 0.5–1.0 mm as input. For thin foil thickness, i.e. 5–20 µm, the final rolling steps are carried out by ‘double-rolling’, i.e. rolling together two foil layers at the same time. During cold rolling, a mineral oil fraction is used for cooling and lubrication. A final annealing treatment is usually applied to the aluminium foil before delivery. Aluminium foil is produced in varying gauges which are mainly used for packaging applications. It is available in thickness from 5 to 200 µm and can be supplied in a range of finishes.

**Profile (extrusion)** Aluminium profiles are produced by the extrusion process, consisting in pushing a hot cylindrical billet of aluminium through a shaped die. The term ‘extrusion’ is usually applied to both the process and the product.

The starting material for aluminium extrusion production is an extrusion ingot (usually called log or billet), i.e. a several-metres-long cylinder with a diameter typically comprised between 150 and 500 mm. These billets are usually produced by DC casting technology. The ends (tops and tails) of the billets are usually sawed at the cast house for direct remelting. Depending on the extrusion presses, the billet needs to be cut in smaller cylinder pieces before the extrusion process. Just before extrusion, the billet is preheated usually around 450–500°C. At these temperatures, the flow stress of the aluminium alloys is very low and by applying pressure by means of a ram to one end of the billet, the metal flows through the steel die, located at the

other end of the container to produce a profile. The profile cross section, which is defined by the shape of the die, can be very complex and can integrate many functionalities. The resulting profile can be used in long lengths or cut into short parts for use in structures like window frames, vehicles or components. Main uses of aluminium extruded products are in building and transport applications.

### 3.3 Aluminium recycling

Most process aluminium scrap comes into the recycling industry directly from the fabrication of semi-finished products and the consumer product manufacturing. It is therefore of known quality and alloy and is often uncoated. It can then be melted with little preparation, apart perhaps from baling. Such scrap are usually collected by the so-called remelters and melted in reverberatory furnaces in order to produce new wrought aluminium alloys. Some new scrap that arises during semi-finishing processes may be coated with paints, ink or plastics. This scrap can be de-coated by passing scrap through an oven or a mesh conveyer whilst hot gases are circulated through the mesh to volatilise or burn off the coating. De-coating is usually the only significant scrap preparation step which can be applied to the scrap input by the remelters. The remelting model addresses this specific recycling route organised through the remelters. No scrap preparation phase is included.

Old aluminium scrap comes into the recycling industry via a very diversified and efficient network of metal merchants and waste management companies which have the technology to recover aluminium from vehicles, household goods, etc. This is often done using heavy equipment such as shredders, together with magnetic separators, to remove iron, sink-and-float installations, or by the use of eddy current installations to separate aluminium from other materials. After collection, sorting and preparation, these old scrap are purchased by the so-called refiners and are usually melted into casting alloys, also called foundry alloys. Refiners recycle not only scrap from end-of-life aluminium products but also, scrap from foundries, turnings, skimmings (dross) and aluminium metallics. The refining model specifically addresses this recycling route organised through the refiners. It includes the scrap preparation phase.

## 4 Goal and scope of the LCI project

The LCI project aims at developing generic European LCI datasets related to aluminium production and transforma-

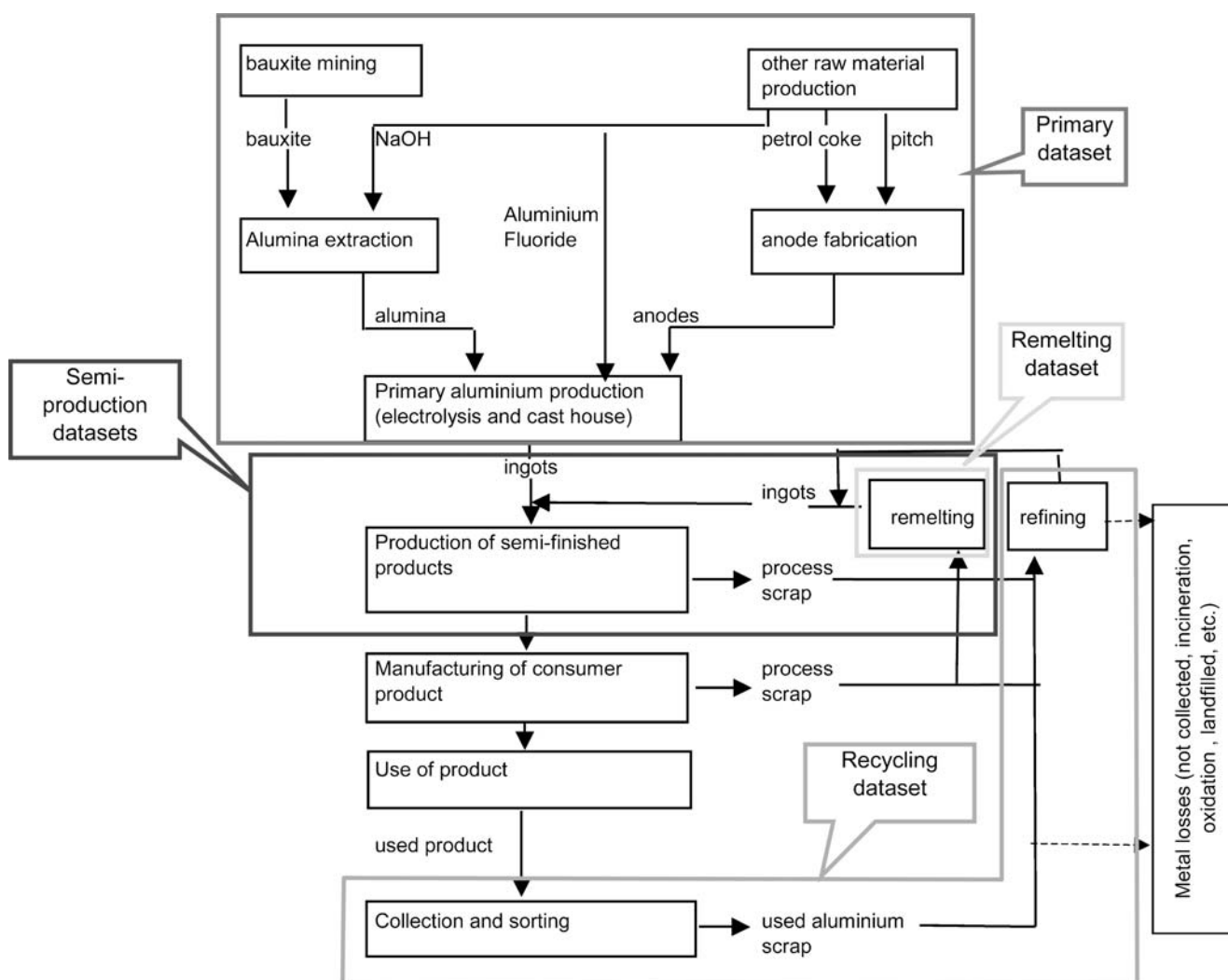
From this survey, the following generic LCI datasets have been developed:

- One dataset on primary aluminium production,
- Three datasets on semi-finished aluminium products fabrication, respectively sheet, profile and foil,
- One dataset on process scrap remelting (remelting dataset),
- One dataset on the recycling of end-of-life aluminium products (refining dataset).

The geographical area covered by these datasets is Europe which is composed of the EU27 and the EFTA countries (Norway, Switzerland and Iceland).

The ‘primary’ LCI dataset corresponds to the production of 1 tonne of ingot from primary aluminium, i.e. from bauxite mining up to the sawn aluminium ingot ready for delivery. This dataset includes all the environmental aspects of the various process steps and raw materials used to deliver 1 tonne of primary ingot to the European market. Since the electricity production is the major contributor to the environmental aspects, a specific electricity model has been developed considering not only the European production but also the primary aluminium imports which represent 36% of the primary aluminium used in Europe in 2005.

The ‘semi-production’ LCI datasets (sheet, foil or profile) correspond to the transformation of an aluminium



**Fig. 2** Process boundaries of the various LCI datasets

ingot into a semi-product, i.e. profile, sheet or foil ready for delivery to the user. These ‘semi-production’ datasets include the recycling of the scrap generated during this semi-fabrication stage as well as the recycling of the dross. The three datasets correspond respectively to the production of 1 tonne of profile, sheet or foil. EAFA (European Aluminium Foil Association, [www.alufoil.org](http://www.alufoil.org)) and EAA worked together for developing the foil dataset.

The ‘remelting’ dataset corresponds to the production of 1 tonne of aluminium ingot from clean process scrap (also called new scrap). This dataset also includes the recycling of dross and skimmings. This dataset should be used for the recycling of process scrap as well as for the recycling of some specific end-of-life products using well-controlled collection schemes like big aluminium pieces from old buildings or dismantled aluminium parts collected through specific collection networks.

The ‘refining’ dataset corresponds to the production of 1 tonne of aluminium ingot from the modelled mix of the European scrap market used by the European refiners, mainly special scrap and end of life scrap. This dataset includes the scrap preparation phase like shredding, cutting, balling, sorting or/and de-coating as well as the melting, purifying and casting operations. It also includes the dross recycling and the salt slag processing. EAA and OEA (Organisation of European Aluminium refiners and remelters) worked together for developing this ‘refining’ dataset.

This generic refining dataset is based on the recycling of the European scrap mix determined according to the ESSUM model (Boin and Bertram 2005). Recycling efficiency and recycling routes highly depend on scrap origin and quality. As a result, for specific aluminium applications or products, it is highly recommended to analyse more closely the recycling scenario(s) and the plausible recycling routes in order to develop more adapted models and associated LCI datasets.

The updated environmental data and the associated LCI datasets, should be used:

- For LCA studies related to products made of or containing aluminium and produced in Europe
- For updating the various environmental and LCI databases related to aluminium processes in Europe

These process-related data have been aggregated at European level and averages representative for Europe have been calculated for the various processes and sub-processes involved in the aluminium production chain. These data provided by the EAA members for their own process steps are the most up-to-date average data available for these processes, and it is recommended that they be used for LCA purposes. Older literature data should be disregarded, as they may no longer be representative due to technological improvements.

To complete the product system under study, the user should collect the following additional data and information:

- Inventory data on the production of components not made of aluminium,
- Inventory data on the fabrication and the assembly of the final product system from semi-fabricated aluminium components and possibly other material pieces,
- Inventory data associated with the use phase of the product system.
- Inventory data related to the end of life treatment, with a special focus on the collection and recycling processes for aluminium.

The development of updated European averages for the various reported process inputs and outputs also aims at evaluating the progresses in term of process efficiency and environmental performances. Whenever possible, these averages have been compared with results of previous European surveys covering the years 1998 and 2002 (EAA 2000). For the primary production processes, European averages have been also compared with global averages which were calculated through two surveys organised by the International Aluminium Institute (IAI), covering respectively the years 2000 and 2005 (IAI 2003, IAI 2007).

## 5 Materials and methods

### 5.1 Survey coverage

Foreground data have been collected with full reference to ISO standards 14040 and 14044 on Life Cycle Assessment. The European aluminium producers and transformers provided input and output data of environmental relevance for their respective production facilities. Table 1 lists the various aluminium processes and sub-processes which have been covered through the survey.

Regarding primary production, bauxite mining is the only process step involved in the production chain which has not been covered by the EAA survey. For this process step, worldwide input and output averages published by the International Aluminium Institute for the year 2005 have been used (IAI 2007). All the other processes involved in the aluminium production and transformation into semi-finished products are covered and constitute the foreground system of the LCI modelling.

Table 2 reports the survey results in term of number of replies and consolidated output tonnage. This consolidated output tonnage is compared to the European production determined from the EAA statistics in order to evaluate the survey coverage.

**Table 1** Processes and sub-processes covered in the EAA survey

LCI dataset	Process	Sub-processes
Primary production	Alumina production	
	Electrolysis and casting	Anode (pre-bake) and paste (Söderberg) production, dross recycling
Production of semi-finished products (from ingot up to the semi-finished product)	Sheet	Ingot sawing and scalping, ingot homogenisation, hot rolling, cold rolling, annealing, finishing and packaging, scrap remelting and casting, dross recycling
	Extrusion	Ingot homogenisation, extrusion, finishing and packaging, scrap remelting and casting, dross recycling
	Foil	Strip casting, ingot sawing and scalping, hot rolling, cold rolling, intermediate annealing, foil rolling, final annealing, finishing and packaging, scrap remelting and casting, dross recycling
Recycling	Process scrap (remelting)	Remelting and casting, dross recycling
	End-of-life scrap (refining)	Scrap preparation, scrap melting, refining and casting, dross recycling, salt slag treatment

Alumina refineries are usually big plants producing between 0.5 and 2 Mt of alumina so that the six sites included in the survey represent about 86% of the European production. From 6.57 Mt of alumina production which is covered by the survey, 89% is used for aluminium production. Survey coverage for European smelters is also excellent since 4.5 Mt of primary production are covered while total European production is estimated to 4.9 Mt in 2005, i.e. 92% coverage. Since anode and paste production is usually integrated within the smelter site, this process is also covered in the same range. Such high coverage is not surprising since, traditionally, the primary aluminium sector is used to report environmental data about their processes.

Regarding semi-finished products fabrication, sheet production is very well represented since the 20 surveyed

plants represent more than 70% of the European production. Foil is quite satisfying since it exceeds slightly 50%. While the number of sites covered is more important for extrusion, i.e. 41 sites, the European coverage reaches about 33%. This lower coverage reflects the small size of the extrusion plants and the higher fragmentation of this sector compared to the aluminium sheet and foil sector.

While the coverage for the remelting sector exceeds 50% with 2.66 Mt of recycled aluminium covered, the coverage of the refining sector is limited to 23%. The limited size of the refining sites and the lower usage of data reporting in this sector are the two major reasons for this low coverage. A next environmental survey addressing the European aluminium refining sector should focus on increasing this coverage rate.

**Table 2** Coverage of the various EAA surveys (reference year 2005)

Production or transformation step	Process or sub-process	No. of replies/sites	Reference flow	Tonnage covered (Mt)	European production (Mt) <sup>a</sup>	Survey coverage
Primary production	Alumina production	6	Alumina	6.57	7.62	86%
	Anode (pre-bake) and paste (Söderberg) production	16 (anode) and 6 (paste)	Anode and paste	2.3	2.55	90%
	Electrolysis and casting (smelters)	27 pre-bake and 8 Söderberg	Primary aluminium ingot	4.5	4.9	92%
Production of semi-finished products	Sheet	20	Aluminium sheet	3.33	4.39	76%
	Extrusion	41	Aluminium extrusion	0.98	2.98	33%
	Foil	14 (foil stock)+10 (foil rolling)	Aluminium foil	0.41	0.80	51%
Recycling	Process scrap (remelting)	15	Aluminium ingot	2.66	5.2 <sup>b</sup>	51%
	End-of-life scrap (refining)	10	Scrap input	0.82	3.5	23%

<sup>a</sup> From EAA statistics, Europe: EU27+EFTA countries

<sup>b</sup> Including in-house scrap

## 5.2 Data collection, consolidation and averaging

The European plants participating in the survey delivered absolute figures of process inputs and outputs for the whole year 2005. Input and output data have been collected through detailed questionnaires which have been developed and refined from the first surveys organised in 1994–1996. In practice, this means that, at least, all material flows going into the aluminium processes (inputs) higher than 1% of the total mass flow (tonnes) or higher than 1% of the total energy input (MJ) have been collected, consolidated and averaged in order to be used as foreground data in the LCI models. All material flows leaving the product system (outputs) accounting for more than 1% of the total mass flow is also part of the system. All available inputs and outputs, even below the 1% threshold, have been considered for the LCI calculation. For hazardous and toxic materials and substances, no cut-off rules were applied.

Expert judgement was used to identify outliers and to select input and output data to be included in the consolidation. As far as possible, before any decision of excluding data, reporting companies have been contacted and outliers have been possibly corrected according to the company feedback. Data consolidation and averaging have been done by the EAA in collaboration with an independent expert. The data collection procedures, the various questionnaires and the consolidated data are part of internal reports which have been submitted to the reviewer for scrutiny. These internal reports have been validated by the EAA Product Stewardship Working Group.

To generate the European averages, a horizontal aggregation was used at process or even at sub-process level. This horizontal aggregation supports the modular approach which allows an easy combination between the process or sub-process and which gives details on the contribution of the various process steps to the complete LCI models.

## 5.3 LCI data modelling tool and principles

The GaBi software version 4 (GaBi 2006) has been used to model and develop the various LCI datasets related to the year 2005. The new LCI models have been developed in collaboration with PE International. Previously, the EAA LCI datasets were produced with the so-called LCA-2 software which was specifically developed for this purpose. The use of the GaBi software allows including additional processes and materials within the system boundaries and also offers more modelling possibilities, especially regarding the integration and the update of background data and processes. As a result, new LCI models have been developed in order to better approach reality. Main differences between the new modelling approach (i.e. year 2005)

and past modelling approach (i.e. years 2002 and 1998) are reported in Table 3.

The geographical boundaries of the LCI project have been expanded in order to reflect the expansion of the European Union. From a geographical area covering ‘EU15+EFTA countries’ in 1998 and 2002, the geographical area of the new model is now expanded to ‘EU27+EFTA countries’.

In order to promote the modularity of the various LCI datasets, i.e. their easy combination, two important principles have been systematically applied in all LCI models. Firstly, all the new LCI models include the recycling of all the process scrap, dross or salt slag which are produced along the production chain. As a result, the aluminium ingot or the aluminium semi-finished product is the only valuable aluminium output and no allocation rules are needed for multiple product outputs. Secondly, alloying elements are substituted by pure aluminium so that the LCI modelling is based on a pure aluminium mass flow. This simplification is reasonable for most of the wrought aluminium alloys which usually contain less than 5% of alloying elements. For cast alloys, it is recommended to the user to analyse more closely the contribution of alloying elements, mainly silicon and magnesium, since such alloying elements usually constitute 5% to 15% of the mass of the casting alloys. This substitution of alloying elements by pure aluminium contributes to the modularity of the datasets addressing semi-finished products since the metal input is only composed of aluminium ingot. In addition, the combination of these two principles allows also tracking the metal loss which is then directly reflected by the difference between the aluminium input and the aluminium output. Since metal preservation is crucial for aluminium, this modelling approach allows identifying the hot spots in the transformation or recycling processes. The various models, developed according to these two principles, are described in the specific sections. These two modelling principles were not applied in the previous models so that LCI results related to 2005 are not fully comparable to the LCI results of the years 1998 and 2002.

The other differences associated with the development of the specific LCI datasets are described in detail in the corresponding sections.

## 5.4 Background data

The main LCI background data used in the models are reported in Table 4.

*Fuels and thermal energy* Many aluminium processes use fossil fuels (natural gas, propane, diesel, heavy fuels, etc.) as thermal energy sources. As a result, it is important to consider properly the LCI data related to the extraction,

**Table 3** Main differences between new and old modelling approaches

	2005	2002 and 1998
Generic differences		
Modelling tool	GaBi software EU 27+EFTA	LCA 2 software EU 15+EFTA
Geographical boundaries	ELCD (2006) and GaBi (2006) (ref years between 2002 and 2005)	BUWAL 1998
Main data sources for background data (ancillary processes)	EU-25 model (GaBi—ref year 2002)	UCPTE model
Electricity production model (excluding smelters)	Substitution of alloying elements by pure aluminium and inclusion of dross recycling and salt slag processing	No substitution of alloying elements and no inclusion of dross recycling and salt slag processing
New model assumptions and principle	Yes	No
LCI data modularity (i.e. easy combination between the LCI datasets)		
Specific differences		
Primary aluminium modelling	Transport modelling European electricity model	Sea, rail and road transport for bauxite and alumina Based on a consolidation of energy sources at European level and the modelling of electricity production based on the consolidated European electricity mix
	Electricity model for imports	Considers only two regions, model based on IAI 1995 statistical report on energy sources and specific grid mix for Russian producers
	Cast house	Based on real conditions considering the recycling of sawn ends, sawn ingot as output
Semi-production (extrusion, rolling, foil)	Production chain	All process steps from ingot up to semi-product, including ingot saving
	Process scrap recycling	The recycling of all the scrap produced along production chain are considered, including the dross and salt slag recycling, sawn ingot as output
Sheet production	Ingot homogenisation	Included in LCI data
Foil production	Modelling	Based 20% on strip casting and 80% on classical production route
	Foil gauge	No distinction between thick and thin gauge
Recycling	Remelting model	Dross recycling and salt slag treatment included
	Refining model	Aluminium scrap input based on ESSUM model (Boin and Bertram, 2005)
		No specific model for scrap flow analysis

**Table 4** Main background data used in the various EAA LCI models

Ancillary process	Origin, reference year and geographical coverage of ancillary LCI data	Use
Fuel supply systems and fuel combustion (natural gas, propane, light fuel, heavy fuel, coal, etc.)	ELCD <sup>a</sup> —year 2002—EU25	All datasets
Electricity production—smelters and associated cast houses	PE International—year 2002 (use of power plant datasets which are specific to the country and to the energy source)	Primary production: smelter and cast house
Electricity supply systems	PE International—year 2002—EU25	All datasets except primary smelter and cast house
Lime production	PE International—year 2000—Germany	Primary production (alumina)
Caustic soda production	PE International—year 2005—Germany—(allocation by mass between chlorine and caustic soda)	Primary production (alumina)
Aluminium fluoride production	PE International—year 2005—Europe	Primary production (smelter)
Petroleum coke production	PE International—year 2003—EU 15	Primary production (anode and paste)
Pitch production	PE International—year 2005—Germany	Primary production (anode and paste)
Transportation (boat)		Primary production (bauxite and alumina)
Solid waste incineration (commercial waste incineration)	PE International—year 2005—Europe	All datasets

<sup>a</sup> ELCD European Life Cycle Data system (<http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm>)

preparation and combustion of these fuels. LCI data reported in the ELCD system developed within the European platform on LCA have been used. These fuel LCI datasets use the lower calorific value of these fuels as reference flow. As a result, all fuel consumption expressed in mass or volume have been converted into MJ, using the lower calorific value of the fuel. By default, the calorific values reported in Table 5 have been used.

Among the surveyed foreground data, main air emissions like particulates, SO<sub>2</sub> and NO<sub>x</sub> have been systematically collected and consolidated. These emissions are mainly linked to the fuel combustion process and are also included in the background ELCD data of fuel preparation and combustion. In order to avoid double counting, background values calculated from the ELCD LCI data have been deducted from foreground values. When the deduction gave a negative value, i.e. background data emissions are higher than reported foreground data, the corresponding foreground data have been fixed to zero.

**Table 5** Default calorific values of fossil fuels

	Calorific values MJ/kg	Density kg/m <sup>3</sup>
Heavy oil	40.50	970
Diesel and light fuel oil	42.70	840
Natural gas	45.75	0.80
LPG (propane)	46.30	2.10

*Electricity* For the primary aluminium production, a new and refined electricity model has been developed for the production of electricity which is consumed within the aluminium smelters (anode production, electrolysis and casting). This model is detailed under Section 6.1.3. For all the other processes, the LCI dataset related to EU25 (reference year 2002) has been used. This LCI dataset assumes 6% of electricity losses. It should be noted that the UCPT model was used previously. This switch has quite a significant impact on the LCI data for semi-finished products fabrication as stressed in Section 6.2.2. The share of energy sources and the main air emissions of the two datasets are reported in Table 6.

### 5.5 Raw materials

For the alumina production, the main raw materials are lime (CaO) and caustic soda (NaOH). German LCI data from PE International have been used for both materials. The other important ancillary raw materials are petroleum coke and pitch used in the anode production as well as, in a lesser extent, aluminium fluoride consumed at the electrolysis step. For these three raw materials, background LCI data from PE International have been used.

*Transport* Only sea transport of bauxite and alumina has been modelled and integrated into the LCI dataset for primary aluminium. No transport data have been integrated into the other LCI datasets.

**Table 6** Energy sources and main air emissions for the UCPTTE and EU-25 electricity model

Electricity model	EU25 (year 2002)	UCPTTE
Share of energy sources		
Hydro	10.3%	16.4%
Hard coal	18.9%	17.4%
Brown coal	10.7%	7.8%
Oil	6.0%	10.7%
Gas	17.3%	7.4%
Nuclear	32.1%	40.3%
Others	4.7%	
Total	100.0%	100.0%
Main emissions (kg/MWh)		
CO <sub>2</sub>	535	429
Dust	0.116	0.512
NO <sub>x</sub> (as NO <sub>2</sub> )	0.99	0.92
SO <sub>2</sub>	2.74	2.26

Bauxite used in Europe is imported, mainly from Guinea, Australia and Brazil. Average transport distance for imported bauxite is about 8,500 km by sea. Average transport distance for the imported alumina to Europe is around 8,000 km by sea. The model also considers 1,000 km as the transport distance for bauxite used in the alumina plants exporting to Europe. No transport distance has been considered for the alumina produced in Europe. This transport model has been used also for bauxite and alumina which are used for the production of primary aluminium which is imported into Europe. Figure 3 summarises the average transport distances used in the 'primary' model.

Considering the European alumina production and 30% of alumina imports, the average sea transport distance of bauxite and alumina are respectively 6,250 and 2,400 km. A specific fuel consumption of 0.54 g of heavy oil per tonne transported and per kilometer has been used (bulk carrier between 10,000 and 200,000 tonnes). As a result, the transport of 1 tonne of bauxite on 6,250 km gives then a consumption of 3.38 kg of heavy oil.

**Solid waste treatment** The various treatments of solid wastes have not been modelled and integrated within the system boundaries, except for solid wastes which are incinerated. In such case, the incineration process has been modelled through LCI data related to commercial waste incineration representative for Europe. This dataset includes energy recovery (steam) and electricity production. Such energy output, representing always less than 5% of the energy demand, is directly recycled within the various LCI models.

In a next survey, specific data will be collected on solid waste processing and treatment in order to be able to model such operations and to integrate them within the system boundaries. As a result, solid waste streams are listed but not tracked in the various LCI datasets.

## 6 Results and discussion

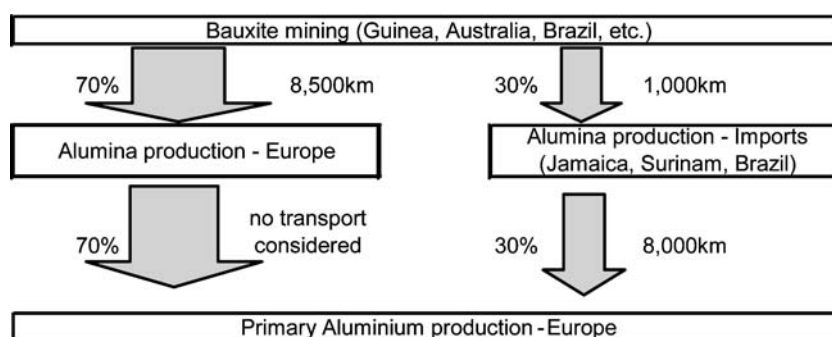
### 6.1 Primary aluminium production

#### 6.1.1 Direct input and output process data

**Alumina production** Most significant input and output data related to the production of 1 tonne of alumina are reported in Table 7. Average European figures of the year 2005 can be compared with figures of the years 2002 and 1998 as well with worldwide figures (survey organised by IAI) for the years 2000 and 2005.

About 2,200 kg of bauxite is used in Europe for producing 1,000 kg of alumina. Bauxite consumption slightly increased since 1998 due to the progressive use of lower grade concentrate. Average bauxite consumption at worldwide level is significantly higher, i.e. around 2,700 kg. Red mud production follows this trend. While 706 kg are produced in Europe in 2005 per tonne of alumina, 1,142 kg are produced at worldwide level.

In 2005, European producers used 67 kg of caustic soda and 43 kg of calcined lime as reactive chemicals per tonne of alumina produced. This consumption slightly increased

**Fig. 3** Average sea transport distances of bauxite and alumina

**Table 7** Main input and output data for the production of 1 tonne of alumina

Area		Europe (EAA)			World (IAI)	
Year		2005	2002	1998	2005	2000
<b>Inputs</b>						
Raw materials						
Bauxite	kg	2,199	2,147	2,138	2,739	2,685
Caustic soda (NaOH 100%)	kg	67	59	60	89	82
Calcined lime	kg	43	47	46	40	45
Fresh water	m <sup>3</sup>	3.25	3.6	3.7	7.9	3.3
Fuels and electricity						
Coal	kg	0	0	8.5	88.4	96
Diesel oil	kg	0.3	19.6	0	0.7	0.6
Heavy oil	kg	204.1	222.4	212	101.4	115
Natural gas	kg	24.0	17.6	26.4	92.8	96.8
Propane	kg	3.0				
Total thermal energy	MJ	9,514	10,649	10,043	10,970	11,925
Electricity	kWh	241	237	230	126	106
<b>Outputs</b>						
Air emissions						
Particulates	kg	0.23	0.21	0.67	0.17	0.63
NO <sub>x</sub> (as NO <sub>2</sub> )	kg	1.22	1.06	1.57	0.88	1.17
SO <sub>2</sub>	kg	3.94	7.59	10.5	3.4	5.3
Water emissions						
Fresh water	m <sup>3</sup>	1.9	2.8	2.3	5.3	3.3
Solid waste						
Bauxite residue (red mud)	kg	706	713	669	1,142	990

in comparison to previous years but the caustic soda consumption is significantly lower than the global average.

Fresh water (3.25 m<sup>3</sup>) enters the process and 1.9 m<sup>3</sup> exits, giving a water consumption of 1.35 m<sup>3</sup> per tonne of alumina, a figure similar to the water consumption calculated in 1998. This water consumption appears lower than the global consumption which reaches 2.6 m<sup>3</sup> in 2005.

Most of the energy use is in the form of thermal energy. About 9,500 MJ is used in 2005 in Europe per tonne of alumina, i.e. about 5% reduction vs. 1998. European producers use mainly heavy oil (204 kg/tonne) as a source of thermal energy while worldwide production is more balanced between coal, heavy oil and natural gas. Electricity consumption is quite stable in Europe around 230–240 kWh. Compared to worldwide averages, thermal energy is lower in Europe while electricity consumption is higher.

With 3.94 kg per tonne of alumina, SO<sub>2</sub> constitutes a major air emission which mainly results from the combustion of heavy oil. However, since 1998, a significant reduction of the SO<sub>2</sub> emission is observed since 10.5 kg was calculated at that time. Particulates emission is also significantly reduced while NO<sub>x</sub> evolution is not fully clear. For these three air emissions, global averages of the year

2005 appear slightly smaller than European averages of the same year.

*Carbon anode and paste production* Most significant input and output data related to the production of 1 tonne of carbon paste and anode mix are reported in Table 8. Average European figures of the year 2005 can be compared with figures of the years 2002 and 1998 as well with worldwide figures for the years 2000 and 2005 (IAI 2003, 2007).

Figures reported in Table 8 refer to an output mix of anode and paste which evolves from year to year according to the aluminium production share of the pre-bake technology using carbon anode vs. the old Söderberg technology using carbon paste. While paste production requests only mechanical mixing, anode preparation also includes anode baking and the associated energy use, air emissions and weight losses. As a result, comparisons with previous years or global averages need to consider also the modification regarding the mix ratio ‘anode/paste’.

Regarding raw carbon materials, recycled butts have contributed less to the production of anodes in 2005 than in 1998 but similarly to 2002. Use of Petrol coke has

**Table 8** Main input and output data for the production of 1 tonne of carbon paste and anode mix

Area		Europe (EAA)			World (IAI)	
Year		2005	2002	1998	2005	2000
Mix ratio (anode/paste)		90/10	88/12	85/15	85/15	81/19
<b>Inputs</b>						
Raw carbon materials						
Petrol coke	kg	737	712	691	N.A.	N.A.
Pitch	kg	173	178	171	N.A.	N.A.
Recycled butts	kg	165	164	188	N.A.	N.A.
Total carbon input		1,075	1,054	1,050		
Other raw material inputs						
Fresh water	m <sup>3</sup>	3.0	1.9	4.3	2.3	2.2
Refractory materials	kg	11	8.8	10.1	6.2	12.5
Fuels and electricity						
Coal	kg	0	4.3	0.0	2.2	2.1
Diesel oil	kg	0.02	2.7	0.2	2.3	3.2
Heavy oil	kg	14.2	16.7	23.1	11.3	14.1
Natural gas	kg	45.9	44.7	41.0	42.3	42.4
Total thermal energy	MJ	2,677	2,987	2,820	2,568	2,721
Electricity	kWh	145	153	131	129	141
<b>Outputs</b>						
Air emissions						
Fluoride gaseous (as F)	kg	0.052	0.087	0.09	0.014	0.046
Fluoride particulate (as F)	kg	0.035	0.063	0.05	0.002	0.01
Particulates	kg	0.21	0.25	0.31	0.207	0.3
NO <sub>x</sub> (as NO <sub>2</sub> )	kg	0.32	0.29	0.24	0.253	0.29
SO <sub>2</sub>	kg	1.54	1.23	0.91	1.95	1.7
Total PAH	kg	0.051	0.062	0.098	0.06	0.055
BaP (benzo[ <i>a</i> ]pyrene)	g	0.14	0.67	3.2	0.08	0.24
Water emissions						
Fresh water	m <sup>3</sup>	2.3			0.9	

increased accordingly (737 kg/tonne) in 2005. Pitch (binder) consumption is quite stable at 173 kg in 2005.

Natural gas is the main fuel used for the anode baking, followed by heavy oil. In 2005, the production of mixed anode and past consumed 45.9 kg of natural gas, 14.2 kg of heavy oil and 145 kWh of electricity. Fuel and electricity consumption in Europe is stable and similar to global figures. However, considering the anode/paste ratio evolution, this stability reflects some energy efficiency improvements.

Fresh water input reaches 3 m<sup>3</sup> in 2005 for 2.3 m<sup>3</sup> of water output. Since big discrepancies exist between the plants, water inputs and outputs figures are not very meaningful. It is not possible to compare the water consumption with previous years since water output was not calculated.

About 11 kg of refractory materials are consumed by tonne of mix anode/paste, a quite stable figure.

Regarding air emissions, particulate fluoride (−55% over 2002) and gaseous fluoride (−60% over 2002) decrease in Europe but are still higher than the world average. The more intensive use of recycled anode butts (contaminated with fluorides) may explain these higher figures as well as possible difference in exhaust fume treatment technology. Since 1998, PAH emissions decrease to the range of the world average. Benzo[*a*]pyrene (BaP) is significantly reduced from 3.2 g/tonne in 1998 down to 0.14 g/tonne in 2005 but the European figure is higher than the global average of 0.08 g/tonne in 2005.

**Electrolysis** Most significant input and output data related to the production of 1 tonne of liquid aluminium at the electrolysis step are reported in Table 9. Average European figures of the year 2005 can be compared with figures of the years 2002 and 1998 as well with worldwide figures (survey organised by IAI) for the years 2000 and 2005.

**Table 9** Main inputs and outputs for the production of 1 tonne of liquid aluminium at the electrolysis step

Area		Europe (EAA)			World (IAI)	
Year		2005	2002	1998	2005	2000
<b>Inputs</b>						
Raw materials						
Alumina	kg	1,925	1,924	1,923	1,923	1,925
Anode and paste (gross)	kg	536	553	557		
Aluminium fluoride	kg	18.9	19.0	18.7	16.4	17.4
Cathode carbon	kg	6.3	10.3	7.5	8	6.1
Other raw material inputs						
Fresh water	m <sup>3</sup>	9.6	5.2		5.3	2.9
Sea water	m <sup>3</sup>	58	69.2		17.6	20.7
Refractory materials	kg	8.6	9.88	8.6	5.4	6.1
Fuels and electricity						
Electricity	kWh	14,914	15,389	15,574	15,289	15,365
<b>Outputs</b>						
Air emissions						
Particulates (total)	kg	2.3	2.33	2.62	3.7	3.3
Fluoride particulate (as F)	kg	0.44	0.41	0.61	0.49	0.5
Fluoride gaseous (as F)	kg	0.56	0.53	0.54	0.55	0.55
NO <sub>x</sub> (as NO <sub>2</sub> )	kg	0.65	0.41	0.16	0.32	0.35
SO <sub>2</sub>	kg	8.2	8.3	8.85	14.9	13.6
Total PAH	kg	0.041	0.031	0.047	0.29	0.13
BaP (benzo[ <i>a</i> ]pyrene)	g	1.3	1.47	2.75	2.6	5
CF <sub>4</sub>	kg	0.087	0.164	0.252	0.13	0.22
C <sub>2</sub> F <sub>6</sub>	kg	0.01	0.014	0.028	0.013	0.021
Water emissions						
Fresh water	m <sup>3</sup>	9.1	4.8		4.9	3.1
Sea water	m <sup>3</sup>	57	69.3		17.6	20.9
Fluoride (as F)	kg	0.62	0.56		0.32	0.2
By-products for recycling						
Anode butts	kg	107	106	109		
SPL carbon fuel/reuse	kg	4.7	7.7	9.6	4.8	9.9
SPL refractory bricks—reuse	kg	4.8	7.9		4	5.5
Solid waste (landfilled)						
SPL—landfill	kg	13.4	19.9	22.9	13.2	17.3

Alumina consumption is stable around 1,923–1,925 kg/tonne. Gross (536 kg/tonne) and net (428 kg/tonne) carbon anode and paste consumption are slightly down from 1998 till 2005. Aluminium fluoride consumption (18.9 kg/tonne) is stable.

European electricity consumption in 2005 reaches 14,914 kWh/tonne, i.e. 4% down compared to 1998. This positive trend results from optimised operating conditions, combined with the progressive phasing out of Söderberg plants which reduce their share in total European production. In 2005, average electricity consumption at global level reaches 15,289 kWh/tonne, i.e. about 2.5% higher than in Europe.

Fresh water is mainly used for cooling but also, in some cases, for wet scrubbing, i.e. for smelter air cleaning systems. Fresh water use highly depends on the location of the smelters since huge discrepancies appear between water-stressed areas and coastal regions. Accordingly, the European average of fresh water input as well as water output are not very meaningful.

Seawater is used for wet scrubbing. This process is relevant to a limited number of companies, but significant quantities are reported, since the principle is based on absorbing smelter air emissions into seawater in harmless concentrations. Accordingly, the average European seawater input cannot be considered as a reliable European average.

In 2005, a total of 1.1 kg of fluoride was emitted to the air in Europe per tonne of electrolysed aluminium, 0.56 kg as gaseous fluoride and 0.44 kg as particulate fluoride, mainly  $\text{AlF}_3$ . These fluoride air emissions are stable in Europe. The emission of all particulates reaches 2.3 kg, i.e. a slight decrease compared to the year 1998.  $\text{NO}_x$  and  $\text{SO}_2$  are emitted through the anode combustion. While  $\text{SO}_2$  is slightly reduced from 8.85 kg/tonne down to 8.2 kg/tonne,  $\text{NO}_x$  is increased from 0.16 kg/tonne up to 0.65 kg/tonne without clear explanations. PAH (polycyclic aromatic hydrocarbons) and BaP (benzo[*a*]pyrene) emissions result mainly from the carbon paste decomposition and incomplete combustion. PAH emission reaches 41 g/tonne in 2005 from which 1.3 g/tonne is BaP. This BaP emission is significantly reduced in Europe compared to 1998. Most dramatic improvements concern PFC (polyfluorocarbons) emission, i.e.  $\text{CF}_4$  (tetrafluoromethane) and  $\text{C}_2\text{F}_6$  (hexafluoroethane) emissions. In 2005, 87 g of  $\text{CF}_4$  and 10 g of  $\text{C}_2\text{F}_6$  were emitted on average in Europe by tonne of electrolysed aluminium while respectively 252 g of  $\text{CF}_4$  and 28 g of  $\text{C}_2\text{F}_6$  were calculated in 1998, i.e. almost 70% reduction between 1998 and 2005. This spectacular reduction in PFC emissions results from a better control of the alumina feeding process which significantly reduces the frequency of the anode effects as well as from the progressive lower contribution of the Söderberg technology to the European mix.

In comparison to global averages, European air emissions are similar for fluorides and lower for all the other emissions, except for  $\text{NO}_x$ . Global averages are significant higher for  $\text{SO}_2$ , PAH and BaP. For PFC emission, European figures are about 30% lower than global average. In 2005, about 10 kg/tonne of spent pot lines (SPL) are sorted into carbon and refractory fractions and are recycled while 13.4 kg/tonne of SPL is landfilled. In Europe, SPL landfilling has been reduced by about 40% in comparison to 1998. These figures are very similar to the global ones.

**Ingot casting** Most significant input and output data related to the production of 1 tonne of sawn ingot at the cast house are reported in Table 10. Average European figures of the year 2005 can be compared with figures of the years 2002 and 1998 as well with worldwide figures (survey organised by IAI) for the years 2000 and 2005.

Aluminium input of the cast house is not only composed of liquid aluminium coming from the electrolysis but consists also in solid metals like alloying elements, aluminium scrap and ingot for remelting, mainly for preparing the right alloy composition. The scrap input is also composed of the ends of the extrusion ingot and rolling ingots which are usually sawn at the cast house location and directly recycled in the casting furnace. In 2005, solid metal input represents about 25% of the metal input.

As already stated for the electrolysis step, water input is highly dependent on the smelter location so that a European average has little significance. Due to inconsistencies, water output has been calculated based on 80% of water input.

Natural gas and heavy oil are the two major fuels used within European cast houses, an average consumption of 20.3 kg of natural gas and 7.7 kg of heavy fuel are calculated for the year 2005. Comparison with the year 1998 is not directly possible since figures related to 1998 have been extrapolated in order to reflect an input of 100% liquid aluminium. The thermal energy consumption at European level is slightly lower than the global average but European cast houses use more electricity but this electricity consumption is small compared to the electricity use at the electrolysis step.

European averages of air emissions at cast house are not very significant since, in many cases, such figures are included in the electrolysis step and no specific figures are given for the cast house. Such air emissions at the cast house are anyway quite small compared to the emission calculated for the electrolysis step.

Most significant by-product is the dross (mix of aluminium oxide and entrapped aluminium metal) which represents 17.8 kg/tonne in Europe. After mechanical hot pressing for extracting most of the liquid metal, the dross is usually recycled internally or externally in rotary furnaces. In Europe, 15.7 kg/tonne of dross is recycled while 2.1 kg/tonne is landfilled.

### 6.1.2 Mass flow modelling

Average input and output data of the year 2005, reported in Tables 7 to 10, are used to model the primary production route by combining such processes along the production chain, i.e. from bauxite mining up to sawn primary ingot. Such process combination requires some simplifications and some adaptations to make the material flow consistent. These adaptations concern the close-loop material flow of the anode butts and the aluminium input of the cast house.

**Anode butt recycling loop** While carbon paste is entirely consumed during the electrolysis process using the Söderberg technology, carbon anode used in smelters using pre-bake technology is not entirely consumed. When about 80% of the anode is consumed, the so-called anode butt is then removed from the cell (and replaced by a new one). This anode butt is then returned to the anode production facility where it is crushed and recycled into the anode production process. In the modelling process, a slight adaptation of the raw material input of the anode

**Table 10** Main input and output data for the production of 1 tonne of sawn aluminium ingot at the cast house

Area		Europe (EAA)			World (IAI)	
Year		2005	2002	1998	2005	2000
<b>Inputs</b>						
Metals						
Liquid aluminium from electrolysis	kg	784	843	832		
Aluminium ingot	kg	99	133	169		
Aluminium scrap	kg	108	35			
<i>Total Aluminium</i>	kg	991	1,011	1,001		
Alloy additives	kg	31	17	11	20	20
Other raw material inputs						
Fresh water	m <sup>3</sup>	3.1	7.5	4.7	4.5	3.15
Sea water	m <sup>3</sup>	0.8	1			0.23
Fuels and electricity						
Coal	kg				1.2	
Diesel oil	kg	0.8		0.1 <sup>a</sup>	1.4	0.1
Heavy oil	kg	7.7		10.9 <sup>a</sup>	5.7	10
Natural gas	kg	20.3		13.9 <sup>a</sup>	24	41.6
Total thermal energy	MJ	1,276		1,082 <sup>a</sup>	1,424	2,312
Electricity	kWh	126		16 <sup>a</sup>	83	81
<b>Outputs</b>						
Air emissions						
Particulates	kg	0.042	0.063	0.0003	0.018	0.1
NO <sub>x</sub> (as NO <sub>2</sub> )	kg	0.17	0.18	0.064	0.11	0.16
SO <sub>2</sub>	kg	0.32	0.62	0.031	0.035	0.29
Water emissions						
Fresh water <sup>b</sup>	m <sup>3</sup>	2.5	6.0			
By-products for recycling						
Dross	kg	15.7	20.5	18.6	13.3	16.0
Solid waste (landfill)						
Dross—landfill	kg	2.1	1.36		2.5	9.7

<sup>a</sup> Figures extrapolated for 100% liquid aluminium as an input

<sup>b</sup> Due to inconsistencies in reporting, water output is calculated on basis of 80% of water input

preparation process was needed in order to make it consistent with the anode butt which comes back from the electrolysis process.

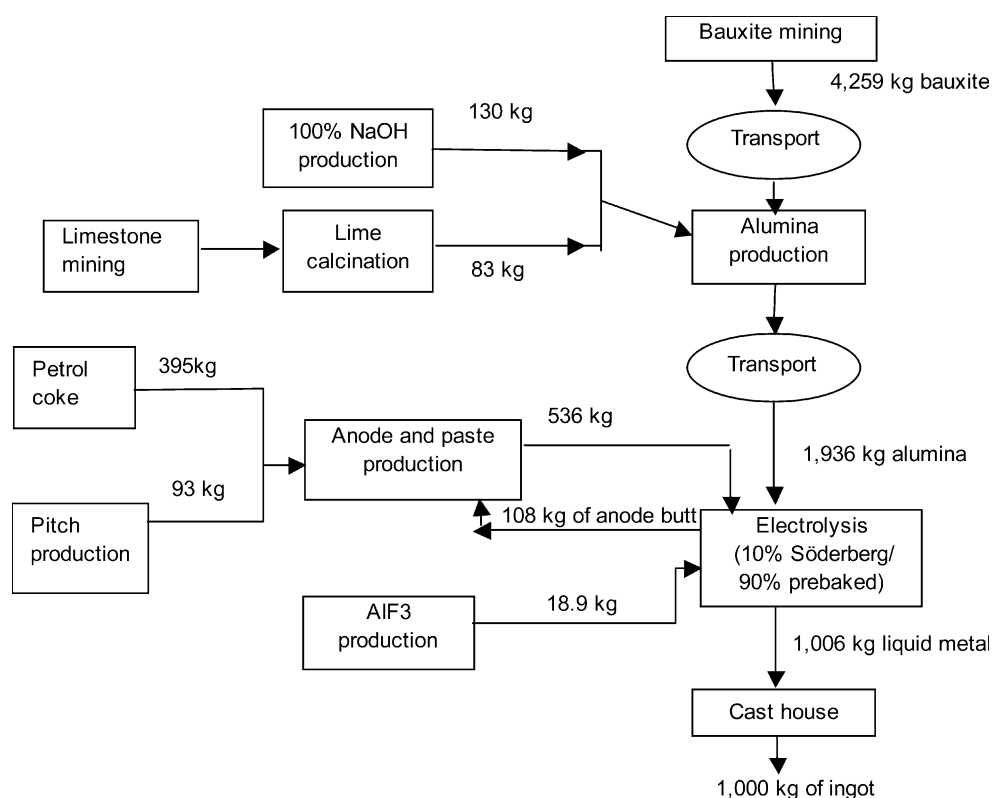
*Metal input at the cast house* For the cast house, it is assumed that the input and output data reported in Table 10 are valid for the modelled aluminium input which is composed of a mix of liquid aluminium from the electrolysis and scrap coming from the ingot sawing operation (between 50 and 100 kg/tonne of ingot). As reminder, alloying elements are substituted by pure aluminium in the model and a small additional aluminium input comes back from the dross recycling process which is included within the system boundaries.

Considering above modelling adaptations, the average consumptions of main raw materials for producing 1 tonne

of aluminium ingot have been calculated and are reported in Fig. 4 and Table 11.

According to the new model, 1,006 kg of liquid aluminium from the electrolysis is needed to produce 1 tonne of sawn ingot. The amount of 6 kg represents the metal losses mainly due to melt oxidation and to unrecovered metal in the dross. In the previous model, 1,001 kg of liquid aluminium was needed to produce 1 tonne of ingot. However, direct comparison with previous years is not possible since substitution of alloying elements by pure aluminium and dross recycling were not considered.

The substitution of alloying elements in the new model also apparently increases the alumina consumption since 1,936 kg are needed per tonne of sawn ingot while 1,923 kg was consumed in 1998. Moreover, 4,259 kg of bauxite is used according to the new model vs. 4,111 kg according to

**Fig. 4** Main raw material inputs for primary aluminium production in Europe

the 1998 model. This bauxite consumption increase is not only due to this new modelling approach but also due to the progressive use of lower grade concentrate. Caustic soda consumption increases of about 15% while lime consumption is slightly reduced. The net anode consumption is slightly reduced compared to previous years.

### 6.1.3 Electricity model for primary aluminium production

Since most of the energy used for producing primary aluminium is electricity at the electrolysis step, it is crucial to model precisely this electricity production. As about one third of the primary aluminium used in Europe is imported,

it is also necessary to take into account specific data relative to the electricity which is used for the production of primary aluminium which is imported to Europe. The two next sub-sections explain how European production and imported primary aluminium are considered to build the EAA electricity model.

*European model: electricity used by European primary aluminium smelters* The European smelters participating in the survey reported their electricity consumption for the year 2005 as well as the share of the various energy sources as stipulated in their electricity contract. These foreground data have been used to develop the European model as described hereafter from a virtual survey based on a simplified consolidation of four smelters located in two countries, the electricity being produced from four energy sources only, i.e. hydropower, nuclear power, natural gas and coal. Table 12 reports the electricity consumption as well as the distribution of energy sources which have been reported by these four virtual smelters for the year 2005. Smelters 1 and 2 are located in country A and smelters 3 and 4 are located in country B. It should be noted that the distribution of energy carriers reported by the smelters can significantly differ from the national grid mix since electricity consumption of the smelters is part of the base load and is usually secured through long-term contracts. Within the same country, the distribution of these energy sources can also differ from smelter to smelter. Figure 5,

**Table 11** Main raw materials for the production of 1 tonne of primary ingot in Europe

Main raw materials (kg)	Process step	Year		
		2005	2002	1998
Bauxite (input alumina)	Alumina	4,259	4,131	4,111
Caustic soda (100%)	Alumina	130	113	116
Lime	Alumina	83	90	88
Alumina	Electrolysis	1,936	1,924	1,923
Anode and paste (net)	Electrolysis	428	447	448
Liquid aluminium	Casting	1,006	1,000	1,001

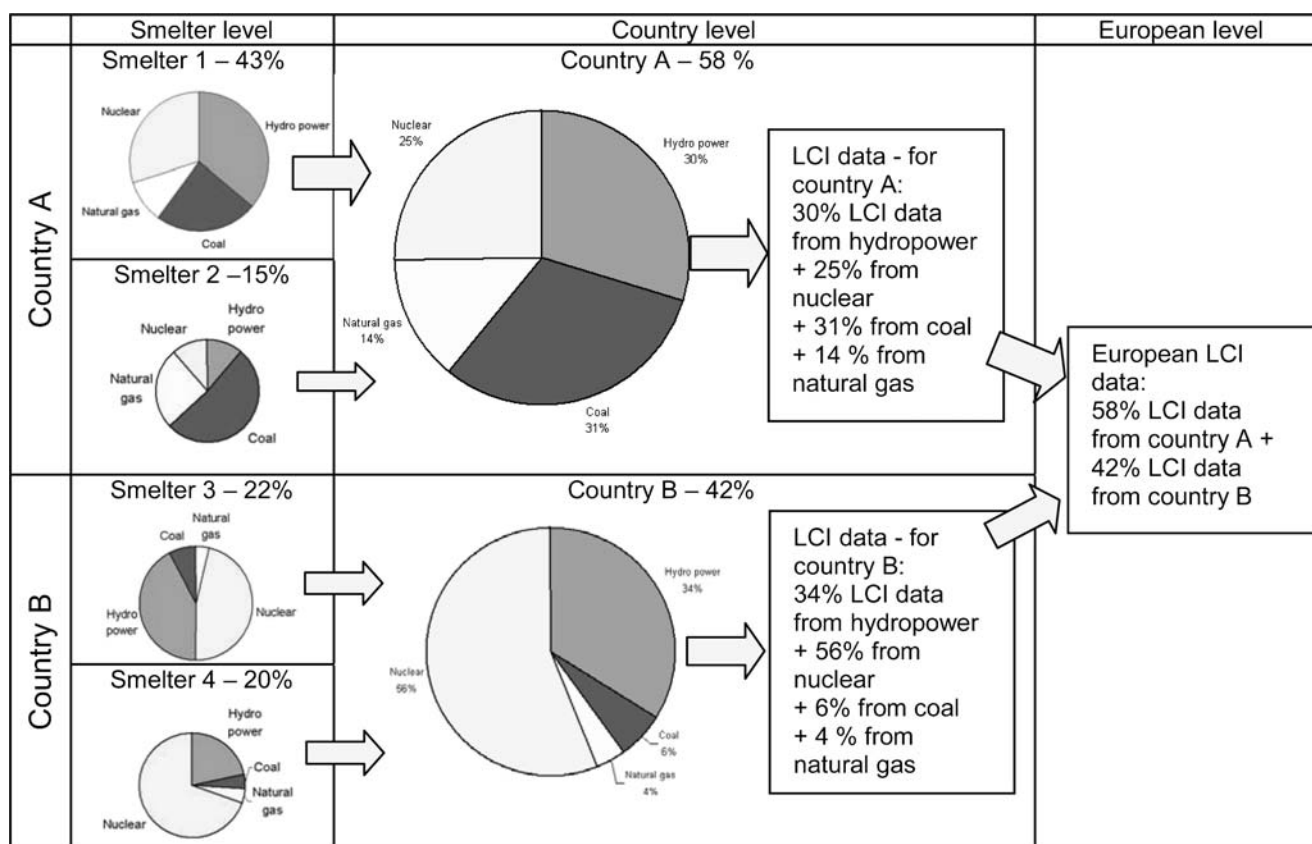
**Table 12** Electricity consumption and energy sources distribution for the virtual consolidation example composed of four smelters in two countries

Virtual example		Electricity consumption year 2005		Distribution of energy sources as stipulated in electricity contracts				
Country	Plant	GWh	% vs. Europe	Hydropower	Coal	Natural gas	Nuclear	Total
A	S1	2,500	43%	36%	24%	10%	30%	100%
	S2	875	15%	11%	51%	26%	11%	100%
	Total	3,375	58%	30%	31%	14%	25%	100%
B	S3	1,300	22%	42%	8%	4%	46%	100%
	S4	1,150	20%	22%	4%	4%	70%	100%
	Total	2,450	42%	33%	6%	4%	57%	100%
Grand total		5,825		31%	21%	10%	39%	100%

which is developed according to the figures reported in Table 12, illustrates how LCI data are calculated at European level. Electricity consumption and energy carriers are firstly consolidated at national level. From this consolidation, the distributions of energy sources at national level are determined. As example, the distribution of energy resources in country A corresponds to 30% hydropower, 31% coal, 14% natural gas and 25% nuclear. The production of electricity is modelled at country level using country-specific and energy source-specific LCI data. The LCI electricity dataset for the country A is then

calculated from the four LCI datasets corresponding to the four types of power plants which are weighted according to their respective contribution to the calculated grid mix. The actual table reporting this consolidation of energy sources at national level cannot be published for confidentiality reasons.

The national LCI datasets are then consolidated at European level using the percentage of their contribution in the total European consumption of electricity. In this virtual example, country A consuming 3,375 GWh in 2005 contributes to 58% and country B consuming 2,450 GWh

**Fig. 5** Principle of the European electricity model based on a virtual example

**Table 13** Country origins of the primary aluminium imports into Europe—average on years 2003, 2004, 2005 and 2006 (source Eurostat)

Area	Import share	Main origins	Contribution	Grid mix used in EAA model	
				Specific	National
Rest of Europe	48%	Russia	80%	x	
		Montenegro	8%	x	
		Bosnia Herzegovina	5%		x
		Ukraine	3%	x	
Africa	23%	Mozambique	71%		x
		Cameroon	9%		x
		South Africa	7%		x
		Egypt	7%		x
Latin America	14%	Brazil	90%		x
Asia	10%	United Arab Emirates	47%		x
		Tajikistan	40%		x
North America	4%	Canada	91%		x
Oceania	1%			Not considered	
Total	100%				

contributes to 42% of the total European consumption. The European LCI dataset is then calculated by the addition of the two consolidated national LCI datasets weighted respectively by these two percentages. The resulting European dataset models the production of 1 MWh of electricity used by the European smelters (see Table 15).

Table 15 reports the European consolidation of the energy sources for the production of electricity which is used by the European smelters. This European distribution of energy sources is not directly used in the new model but is given for comparison purpose with previous years' models. With a share of 44.9% in 2005, hydropower is definitely the major energy source which shows an absolute increase of more than 4% compared to the year 1998. This increase results mainly from production expansion within hydropower-based countries, i.e. mainly Norway and Iceland. With a share of 21.9%, nuclear power stays the second most significant source of energy, even if a slight

decrease is measured since 1998. The use of hard and brow coal is significantly reduced since their share is limited to 19.6% in 2005 while it raised 24.2% in 1998. Oil is also significantly reduced from 5.1% in 1998 to 2.7% in 2005. The only fossil fuel which is more intensively used is natural gas since its share has almost doubled from 5.5% in 1998 up to 9.8% in 2005. This modification of energy sources distribution influences positively the environmental profile of the corresponding electricity production as shown in Table 16 which reports primary energy resources and main air emissions associated with the new and previous European models of electricity production.

*Imports model: electricity used for the production of imported aluminium* In 2005, 36% of the primary aluminium used in Europe (i.e. EU27 and EFTA countries) came from imports. This figure has been calculated from average customs statistics (source Eurostat) on 4 years from 2003

**Table 14** Distribution of energy sources for the electricity imports model

Area	Import share	Share of energy resources for electricity production						
		Hydropower	Coal	Oil	Natural gas	Biomass	Nuclear	Total
Rest of Europe	48%	88.4%	2.9%	0.1%	4.3%	0.0%	4.3%	100%
Africa	23%	85.6%	6.9%	1.6%	5.8%	0.0%	0.4%	100%
North America	4%	58.0%	17.0%	3.0%	6.0%	1.0%	15.0%	100%
Latin America	13%	84.0%	2.0%	3.0%	5.0%	4.0%	2.0%	100%
Asia	10%	45.1%	0.0%	1.1%	53.9%	0.0%	0.0%	100%
Oceania	1%	Not considered in the imports model						
Consolidation		81.5%	4.0%	1.0%	9.8%	0.6%	3.1%	

**Table 15** Distribution of the energy sources for the European model, the imports model and the combined EAA electricity model

Year	European model			Imports model			EAA model		
	2005	2002	1998	2005	2002	1998	2005	2002	1998
Contribution to EAA model	64%	68%	61%	36%	32%	39%			
Distribution of energy sources									
Hydro	44.9%	45.7%	40.6%	81.5%	67.9%	71.4%	58.0%	52.8%	52.61%
Hard coal	14.8%	15.8%	17.5%	4.0%	26.4%	23.8%	10.9%	19.2%	19.96%
Brown coal	5.8%	6.7%	7.7%		0.0%		3.7%	4.6%	4.70%
Oil	2.7%	4.8%	5.1%	1.0%	0.0%	0.4%	2.1%	3.3%	3.25%
Gas	9.8%	7.6%	5.5%	9.8%	4.2%	3.6%	9.8%	6.5%	4.78%
Nuclear	21.8%	19.4%	23.6%	3.1%	1.4%	1.1%	15.0%	13.6%	14.83%
Other (biomass)	0.2%			0.6%			0.3%	0.0%	0.00%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.00%

until 2006 in order to remove any influence of year-specific data inconsistent with the overall trend. As reported in Table 13, most of these imports come from Russia (39%), Mozambique (16%) and Brazil (12%).

Table 13 is used to model the electricity production for the primary aluminium imported into Europe. Only countries listed in Table 13 have been considered for the imports model. These countries represent more than 90% of the aluminium imported into Europe. The various steps and hypotheses of this modelling methodology are the following:

1. Use of the national electricity grid mix for the countries listed in Table 13, except for Russia, Montenegro and Ukraine for which specific data provided by the aluminium producers have been used. Data from the International Energy Agency (reference year 2005) have been used to determine the national grids of the electricity production (IEA 2008).
2. Weighting and consolidation of the national or specific grid mixes at regional level for the five regions exporting

to EU27 and EFTA countries, i.e. rest of Europe, Africa, Latin America, Asia and North America. Oceania is neglected within this consolidation. The consolidated regional electricity grid mixes are reported in Table 14.

3. For each of these regions, modelling of the electricity production based on the consolidated regional electricity grid mixes, using LCI data of power plant which are representative for the region, e.g. electricity from natural gas in Latin America uses Brazilian data or electricity from coal in Africa uses South African data.
4. Consolidation of the electricity production data at global level.

This imports model uses a similar methodology as the European model. The main differences are the following:

- In absence of smelter specific data, the imports model is mainly based on the distribution of energy source calculated according to the official national electricity grid mixes.

**Table 16** Energy resources and air emissions for the production of 1 MWh of electricity according to the European and EAA models

Year		European model			EAA model		
		2005	2002	1998	2005	2002	1998
Fossil-based energy resources							
Brown coal (crude)	kg	64.6	100	130	41.4	67.0	78
Hard coal (crude)	kg	58.0	61.0	68.0	45.9	72.0	76
Natural gas (crude)	kg	24.1	16.8	12.8	25.0	13.6	10
Crude oil	kg	8.3	15.0	16.0	6.1	10.3	11
Main air emissions							
CO <sub>2</sub>	kg	300	347	367	276	348	354
CO	kg	0.10	0.06	0.06	0.09	0.06	0.05
SO <sub>2</sub>	kg	1.02	1.60	2.29	0.87	1.50	1.89
NO <sub>x</sub> (as NO <sub>2</sub> )	kg	0.51	0.74	0.76	0.49	0.79	0.79
CH <sub>4</sub>	kg	0.64	0.88	0.86	0.56	1.10	1.07
Dust	kg	0.07	0.43	0.43	0.06	0.48	0.48

- The modelling of the electricity production is done at regional level while it has been done at national level for the European model.
- The five regional LCI datasets are weighted according to the share of their primary aluminium imports to Europe while European countries were weighted according to their respective electricity consumption.

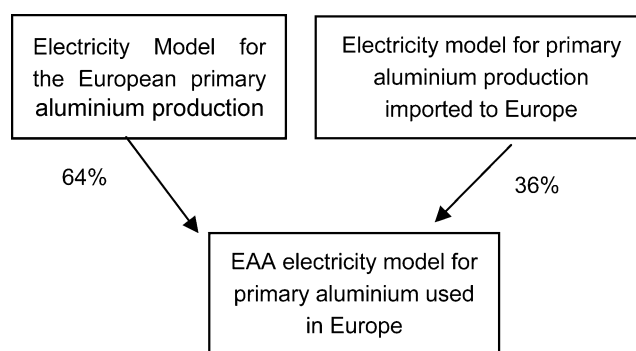
Table 14, reporting the distribution of energy sources calculated from the imports model, clearly shows that imported aluminium is mainly produced through hydropower-based electricity, especially for the imports from Africa, Latin America and the rest of Europe. Global consolidation gives a hydropower share of 81.5%, followed by natural gas with 9.8%. Coal-based electricity production reaches only 4% while nuclear stands only for 3.1%. Oil and biomass are only marginal, i.e. respectively 1% and 0.6%.

As reported in Table 15, this new distribution of energy sources is dramatically modified in comparison to the corresponding distributions calculated in 1998 and 2002 with the previous imports model. On one side, hydropower share increases from 71% in 1998 to 81.5% in 2005 while the coal-based electricity moves from 23.7% in 1998 down to only 4% in 2005. On the other side, the share of natural gas is significantly increased from 4.6% up to 9.8%. This big alteration of the energy sources distribution is mainly due to the difference between the new and old modelling methodologies. In previous model, only two regions, i.e. Russia and ‘Western World’ (excluding Europe), have been considered without analysing the exact origins of the imported aluminium. While Russia presents a similar distribution in the old and new models, the hydropower share of the ‘Western World’ region was calculated to 61% while the new refined methodology gives about 75%. This big increase reflects that aluminium imports to Europe come mainly from hydropower-based countries like Mozambique, Brazil, Cameroon, Canada and Tajikistan. The limited use of coal for the electricity production in such countries explains the big reduction of the coal share within the imports model.

Based on the energy survey of the year 2005 organised by the International Aluminium Institute and based on the structure of the primary imports, the calculation of the specific electricity consumption at the electrolysis step gives 15,227 kWh/tonne for the imported aluminium, excluding the assumed 2% of transmission losses.

**EAA electricity model** Figure 6 schematises the EAA electricity model combining 64% of European production and 36% of primary aluminium imports.

Table 15 reports the share of the various energy sources for the European model, imports model and consolidated



**Fig. 6** EAA electricity model

EAA electricity model. Figures related to the previous model developed for the years 1998 and 2002 are also reported.

With a share of 58%, hydropower appears clearly as the most significant source of energy according to the new EAA electricity model, corresponding to a significant increase compared to previous years since 52.4% and 52.8% were calculated respectively in 1998 and 2002 according to the previous model. Both models, i.e. the European model and imports model, contribute to this positive trend. While coal, i.e. hard and brown coal, represented about 25% in 1998, it contributes only to about 15% as energy source in 2005. Natural gas becomes a more significant energy source since its share raises from 4.8% up to 9.8%. The nuclear energy stays stable around 15%. Oil and biomass are marginal.

**LCI data for electricity** The GaBi software was used to generate the LCI data according to the described EAA electricity model. In most cases, LCI background data related to the year 2002 have been used. These LCI data were energy source and country specific. Fossil-based energy resources and main air emissions for the production of 1 MWh according to the European model and the EAA model are reported in Table 16.

Significant reductions in term of air emissions and fossil-based primary energy consumption are observed in comparison to the years 1998 and 2002. Only the consumption of natural gas increases while the use of all the other fossil-based primary energy resources is significantly reduced. This is particularly the case for the EAA model due to the big reduction of coal consumption. Due to the significant lower share of coal-based electricity in the new model, the CO<sub>2</sub> emission is then significantly reduced since 276 kg of CO<sub>2</sub> per MWh is calculated in 2005 against 348 kg in 2002 or 354 kg in 1998. This reduction of 22% is due to the lower share of fossil-based energy, especially coal, and the improved efficiency of power plants. In parallel, SO<sub>2</sub>, NO<sub>x</sub>, CH<sub>4</sub> and dust air emissions are also significantly reduced.

As a result, the evolution of these background LCI data related to electricity production has a significant influence on the environmental profile of the primary production dataset as highlighted in the next section.

#### 6.1.4 LCI data for primary aluminium

The GaBi software was used to calculate the European LCI dataset for primary aluminium in accordance with the modelling hypotheses previously described. European averages of the year 2005, as reported in Tables 6 to 10, have been used for the model. The only exception concerns air emissions of the electrolysis step for the imported aluminium. In such case, worldwide IAI data of the year 2005 have been used. The full LCI dataset is available on request at [lcj@eaa.be](mailto:lcj@eaa.be). Table 17 reports the main LCI data related to 1 tonne of primary aluminium, i.e. main raw mineral resources and fossil-based energy resources as well as main air emissions. For the year 2005, these data are distributed among the following five process categories:

1. Direct process: direct material consumption/use or direct emissions associated with the primary production, i.e. mainly bauxite and anode/paste consumption.

2. Auxiliary: all ancillary processes and materials used in the aluminium processes, i.e. mainly caustic soda, lime and aluminium fluoride.
3. Electricity: all the processes and materials needed to produce the electricity directly used by the aluminium processes. It includes fuel extraction and preparation. Smelters, i.e. electrolysis, anode/paste production and cast house, use the LCI data calculated according to the EAA model while other processes, i.e. alumina production and bauxite mining, use the EU25 LCI data.
4. Thermal energy: all the processes and materials needed to produce the thermal energy directly used in the aluminium primary processes, excluding pitch and coke used for the anode production.
5. Transport: sea transport of bauxite and alumina.

According to the new model, 4,272 kg of bauxite is needed to produce 1 tonne of primary aluminium, most of this bauxite being used for the alumina production, i.e. 4,259 kg. With respectively 262 and 113 kg, limestone and sodium chloride are the two other major raw mineral materials which are consumed for the primary aluminium production. For limestone, comparison with 2002 and 1988 figures is not possible since previous figures do not

**Table 17** Main LCI data for the production of 1 tonne of primary aluminium used in Europe

Year	2005						2002	1998
	Total	Direct process	Auxiliary	Electricity	Thermal energy	Transport	Total	Total
<b>Main raw materials (kg)</b>								
Bauxite	4,272	99.7%	0.3%	0%	0%	0%	4,131	4,111
Limestone (calcium carbonate)	261.5	1%	68%	27%	27%	4%	162	159.4
Sodium chloride	112.6	0%	100%	0%	0%	0%	87	89
<b>Fossil-based energy resources (kg)</b>								
Crude oil	762	37%	2%	13%	45%	3%	1,381	1,369
Hard coal (crude)	892	12%	4%	83%	1%	0%	1,360	1,464
Brown coal (crude)	756	1%	9%	89%	0%	0%	1,144	1,328
Natural gas (crude)	650	4%	4%	62%	29%	0%	445	408
<b>Main emissions to air (kg)</b>								
Carbon dioxide—CO <sub>2</sub>	8,566	21%	4%	54%	21%	1%	10,521	10,634
Nitrogen oxides—NO <sub>x</sub>	14.0	9%	3%	58%	19%	10%	24	27
Sulphur dioxide—SO <sub>2</sub>	34.2	34%	2%	44%	18%	2%	66.3	72
Methane—CH <sub>4</sub>	14.3	14%	4%	64%	17%	0%	21	20
Fluorides (particles)	0.55	100%	0%	0%	0%	0%	0.44	0.49
Hydrogen fluoride—HF	0.60	94%	0%	5%	0%	0%	0.71	0.75
Group PAH to air	0.151	100%	0%	0%	0%	0%	0.066	0.1
Benzo[a]pyrene	0.0024	100%	0%	0%	0%	0%	0.0018	0.0032
Tetrafluoromethane—CF <sub>4</sub>	0.109	100%	0%	0%	0%	0%	0.16	0.252
Hexafluoroethane—C <sub>2</sub> F <sub>6</sub>	0.010	100%	0%	0%	0%	0%	0.014	0.028

include the consumption for electricity production and fuel preparation. The increase of sodium chloride consumption is due to the higher caustic soda consumption and to the new LCI data related to caustic soda production.

A consumption of 762 kg of crude oil, 892 kg of hard coal, 756 kg of brown coal and 650 kg of natural gas has been calculated in 2005 per tonne of primary aluminium. Crude oil is mainly used for producing the fuels (45%) and the petrol coke for the anode production (37%). Hard coal and brown coal are mainly consumed for the electricity production, respectively 83% and 89% of their use. The use of natural gas is shared mainly between electricity production (62%) and thermal energy source (29%). Compared to the year 1998, the consumptions of brown coal, hard coal and crude oil in 2005 have been reduced respectively by 43%, 39% and 44% while natural gas consumption is increased by 59%. This gives a consolidated consumption of fossil-based primary energy which is considerably reduced in 2005 in comparison to 1998 or 2002. This spectacular reduction results mainly from the refined electricity model which relies more on hydropower-based electricity and from the better efficiency of fuel-based power plant compared to BUWAL data (BUWAL 1998) used in the previous modelling approach. The reduction of electricity consumption (4% vs. 1998) at the electrolysis step, the lower anode consumption (4% vs. 1998) and the lower thermal energy use at the alumina production (5% vs. 1998) also contribute to this decrease in fossil-based primary energy.

In 2005, 8,566 kg of CO<sub>2</sub> emission is calculated per tonne of primary aluminium. This CO<sub>2</sub> emission comes mainly from the electricity production (54%), the fuels used in the aluminium processes (21%) and the anode and paste combustion (21%). This updated CO<sub>2</sub> emission figure corresponds to a significant reduction of almost 20% compared to 1998 or 2002 since 10,634 kg and 10,521 kg of CO<sub>2</sub> were calculated respectively for these two previous years. A significant reduction is also observed for the NO<sub>x</sub> since 14 kg of NO<sub>x</sub> is calculated for 2005, 58% coming from the electricity production, while 27 kg was calculated in 1998. SO<sub>2</sub> is also reduced in the same range since 34 kg are calculated in 2005 for 72 kg in 1998.

Regarding specific emissions associated with the aluminium processes, fluoride emissions (HF and fluorides) are stable. While PAH and BaP emissions are reduced for the European smelters compared to 1998 (see Table 9), this decrease is not reflected in PAH and BaP figures reported in Table 17 due to the detrimental contribution of the PAH and BaP air emissions of the imports. PFC emissions, i.e. C<sub>2</sub>F<sub>6</sub> (hexafluoroethane) and CF<sub>4</sub> (tetrafluoromethane), are significantly reduced by about 60% since 1998.

## 6.2 Semi-finished products fabrication

### 6.2.1 Process data consolidation and averaging

#### Production route determination:

The three generic datasets related to semi-finished products are based on production routes combining the sub-processes which transform the aluminium ingot into an aluminium sheet, foil or profile and which include also the close-loop recycling of the process scrap which are produced along these production routes. In order to develop robust LCI datasets, it is then crucial to calculate precisely the input and output data at sub-process level as well as the process scrap production.

The data consolidation and averaging are particularly critical for the semi-finished products fabrication stage since it is based on production facilities integrating many sub-processes and many types of aluminium inputs and semi-finished product outputs. As example, the aluminium input of a rolling mill, which has an integrated cast house, is usually composed not only of rolling slabs but also of aluminium scrap, ingot for remelting and alloying elements. In this case, the cast house is used not only for the internal process scrap recycling but also for the production of rolling ingot from external aluminium scrap and from ingot for remelting. Some rolling mills also produce aluminium plates as semi-products. The aluminium output of some rolling mills can be composed of hot rolled strip which are then cold rolled in another location. Some rolling mills also include surface treatment and coating lines in their site. Some extrusion plants are also equipped with anodising and surface coating lines. As a result, in order to be able to model properly the production route of the semi-finished products, the data consolidation needs to be performed at sub-process level. Table 18 reports the processes and the sub-processes which have been included in the production route of the three semi-finished products.

In practice, several sites delivered only aggregated data for some inputs and outputs, especially energy use, air emission and waste. For each of these sub-processes, the reference flow, i.e. the aluminium product output, was carefully calculated while a methodology was systematically applied to distribute all the unallocated data to these various sub-processes before averaging.

*Process scrap production* For the semi-production processes, it is also crucial to evaluate precisely the process scrap which are produced along the production route. The aluminium mass flow was carefully tracked along all the sub-processes listed in Table 18 in order to determine the process scrap production per tonne of aluminium output at each sub-process level. The cumulative production of process scrap along the semi-production route was then calculated based

**Table 18** List of processes and sub-processes included in the three datasets for semi-finished products

Dataset	Processes included	Sub-processes included
Sheet	Sheet production	Ingot scalping, ingot homogenisation and pre-heating, hot rolling, cold rolling, annealing, finishing and packaging
	Process scrap recycling (sheet)	Process scrap remelting (including dross recycling and salt slag processing), ingot sawing
Foil	Foil production	– Foil stock production – 80% classical route: ingot scalping, ingot pre-heating, hot rolling, cold rolling, intermediate annealing – 20% strip casting route: strip casting, rolling, intermediate annealing – Foil production: foil rolling, final annealing, finishing and packaging
	Process scrap recycling (foil)	Process scrap remelting (including dross recycling and salt slag processing), ingot sawing
Extrusion	Extrusion production	Ingot homogenisation and pre-heating, extrusion, drawing and finishing, extrusion scrap remelting, die cleaning
	Process scrap recycling (extrusion)	Process scrap remelting (including dross recycling and salt slag processing), ingot sawing

on the combination of the process scrap produced at each of the successive sub-processes. These cumulative productions of process scrap are reported in Table 19 for 1 tonne of semi-finished products. For the year 2005, the consolidation gave 383, 595 and 318 kg of cumulative process scrap respectively for the sheet, the foil and the extrusion. As example, this means that, for producing 1 tonne of foil, 1,595 kg of aluminium ingot is required on average, 595 kg of process scrap being produced in parallel. The LCI models include the close-loop recycling of these process scrap as well as the dross recycling and salt slag processing so that all the aluminium metal is directly recycled. As a result, instead of 1,595 kg of aluminium ingot at the input side, the LCI model reports an aluminium input which corresponds to the aluminium output plus the possible metal losses along the production route and the process scrap recycling.

*Direct input and output data* Table 19 reports the direct average input and output data for the fabrication of 1 tonne of semi-finished product, i.e. from sawn ingot up to the semi-finished product, including the remelting of the process scrap. Direct inputs and outputs associated with dross recycling are not included but the reported aluminium input considers the metal recovered from this dross recycling operation.

Regarding process scrap production, 1998 and 2002 models consider all the process scrap produced along the semi-production chain, including the ingot sawing operation which produces about 60 kg of scrap per tonne of sawn ingot. The 2005 model integrates such scrap production in the cast house operation so that ingot sawing is not included any longer in the process scrap produced along the semi-production chain. As a consequence, a comparison

with previous years is only meaningful if the scrap from sawing operation is added to the cumulative process scrap production calculated for the year 2005. This calculation gives a cumulative scrap production from unsawed ingot up to finished products which reaches 466, 691 and 403 kg respectively for sheet, foil and extrusion in 2005. Comparison with figures of the years 1998 and 2002 shows a significant decrease of process scrap production, particularly for extrusion and foil production. In comparison to 1998, a decrease of about 30% is observed for extrusion since 577 kg of process scrap were calculated in 1998 per tonne of extrusion. For foil production, referring to 990 kg of scrap for the fabrication of thin gauge foil in 1998, a reduction of 30% is observed. This diminution of scrap production reaches about 15% if 823 kg of scrap produced for thick gauge foil is used as a reference in 1998. These reductions demonstrate significant progresses in process efficiencies.

Based on the metal losses linked with process scrap recycling and with the semi-production chain, the aluminium inputs have been calculated. These metal losses reach for sheet, foil and extrusion, respectively 4, 7 and 8 kg per tonne of semi-product. As a result, the model gives an aluminium ingot input of 1,004 kg for sheet, 1,007 kg for foil and 1,008 kg for extrusion. For sheet and foil production, these aluminium losses are mainly associated with the process scrap recycling. For extrusion, the die cleaning operation also generates some metal losses in addition to those linked with the process scrap recycling. Comparison with previous years regarding the metal input and metal losses is not possible since dross recycling was not included in the previous models. However, the lower production of process scrap along the semi-production chain which is calculated in 2005 in comparison to 1998

**Table 19** Main input and output data for the fabrication of 1 tonne of semi-finished product from aluminium ingot (including the process scrap remelting)

Figures for 1tonne of aluminium semi-finished product output		Sheet			Foil	Thin foil <sup>a</sup>	Thick foil <sup>a</sup>	Extrusion		
Year	Unit	2005	2002	1998	2005	1998		2005	2002	1998
Aluminium inputs										
Aluminium ingots	kg	1,004	1,012	1,012	1,007	1,032	1,027	1,008	1,013	1,013
Aluminium intermediate products										
Clean scrap produced and recycled	kg	383	508	477	595	990	823	324	526	577
Dross/skimmings <sup>b</sup>	kg	16.4			24.5			10		
Aluminium outputs										
Dross/skimmings <sup>b</sup>	kg		19	16		33	27.7		15.3	18.4
Finished cold rolled sheet	kg	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Energy inputs (fuels and electricity)										
Heavy oil	kg	1.0			4.6			0.4		
Diesel and light fuel oil	kg	4.8	3.2	0.75	26.6	16	5.9	1.4	1.25	0.65
Natural gas	kg	68.8	89	94.4	138	167	132	73.3	81	101
Propane	kg	1.0			1.7					
Total thermal energy	MJ	3,441	4,201	4,349	6,599	8,323	6,291	3,619	3,904	4,827
Electricity	kWh	726	600	667	1,593	1,936	1,605	876	913	1,321
Ancillary products, inputs										
Argon	kg	0.86	1	0.91	1.43	1.9	1.6	0.73		0.53
Emulsion, hot rolling (oil content)	kg	1.46			2.70					
Oil, cold rolling	kg	3.83	2.4	3.8	24.1	41	31			
Acids, calculated as 100% H <sub>2</sub> SO <sub>4</sub>	kg							6.9		
Alkalis, calculated as 100% NaOH	kg							11.3	15	28
Water inputs										
Water	m <sup>3</sup>	10.2	10.1	42	16.1	124	100	5.9	11	30
Emissions to air										
Carbon monoxide (CO)	kg	0.50			0.47					
Dust/particulates, total	kg	0.03			0.33			0.04		
NO <sub>x</sub> , as nitrogen dioxide	kg	0.35			1.07			0.37		
SO <sub>2</sub>	kg	0.04			0.32			0.03		
VOC	kg	0.38	0.45	0.44	2.22	12	6.4	0		
Organic hydrocarbons (not included in VOC)	kg	0.37			0.29					
Emissions to water										
Water output	m <sup>3</sup>	5.8			9.4			4.7	9	26
Hazardous waste (excluding dross)										
Spent caustic bath/sludge for landfilling	kg							3.6	33	29
Spent caustic bath/sludge for further processing	kg							21.6		
Hazardous waste for landfilling	kg	2.2	7.2	4.8	2.9	14.0	11.0	1.8	2.4	1.6
Hazardous waste for incineration	kg	2.2	2.4	2.3	2.8	10.0	9.8	1.8	2.2	1.7
Hazardous waste for further processing	kg	7.7		0.0	24.8			9.3		
Total hazardous waste	kg	12.2	9.6	7.1	30.5	24.0	20.8	38.1	37.6	32.3
Non-hazardous waste (excluding aluminium scrap, dross/skimmings and demolition waste)										
Non-hazardous waste for landfilling	kg	1.9	11.7	6.5	5.0	21.0	16.0	3.8		
Non-hazardous waste for incineration	kg	0.7	0.0	0.0	0.9	0.0	0.0	2.2		
Non-hazardous waste for further processing	kg	5.3			10.4			9.0		
Total non-hazardous waste	kg	7.9	11.7	13.6	16.3	21.0	16.0	15.0	19.0	23.0

<sup>a</sup> Thin gauge is between 5 and 20µm, thick gauge is between 20 and 200µm<sup>b</sup> Dross recycling not included in 1998 and 2002 but included in 2005 model

and 2002 leads inevitably to lower metal losses associated with their recycling.

Regarding energy, extrusion and sheet are in the same range of thermal energy and electricity uses. While sheet production consumes 3,441 MJ of fuels and 726 kWh, the consumptions for extrusion production are slightly higher since 3,619 MJ of thermal energy and 876 kWh of electricity are calculated. Energy consumption for foil production is about doubled in comparison to sheet production since thermal energy use reaches 6,599 MJ and electricity consumption reaches 1,593 kWh. Compared to previous years, sheet production requires about 20% less thermal energy than in 1998 but about 10% more electricity. For foil, the new collected data do not allow distinguishing between thin and thick gauges as it has been done in 1998 model. Since down gauging of aluminium foil is a heavy trend for several years, it makes more sense to compare the 2005 data with the thin gauge foil data of the year 1998. Based on these 1998 data related to thin gauge foil, a reduction of about 20% of thermal energy and electricity uses are calculated between 1998 and 2005. For extrusion, the reduction of energy use in comparison to 1998 is even more significant since thermal energy is down by 25% and the electricity by more than 30%. These energy reductions demonstrate significant progresses in term of energy efficiency, especially for aluminium extrusion.

Water is mainly used for cooling purposes. The water input for sheet, foil and extrusion are respectively 10.2, 16.1 and 5.9 m<sup>3</sup> while the water output reaches respectively 5.8, 9.4 and 4.7 m<sup>3</sup>. This gives a respective water consumption of 4.4, 5.7 and 1.2 m<sup>3</sup>. It should be emphasized that such water figures are not always fully consistent since some plants reported water outputs which are higher than water inputs. In addition, there are big discrepancies in water use between the plants depending on their location. Nevertheless, comparison with previous years clearly shows a reduction in water use.

Argon is used as protective gas for the scrap remelting operation. Main ancillary compound for sheet and foil production is oil which is used as lubricant and cooling media during the rolling process. The use of oil in hot rolling and cold rolling reaches respectively 1.46 and 3.83 kg per tonne of sheet. This later figure is stable compared to 1998. Foil production consumes much more oil than sheet production since about 26.8 kg of oil is consumed on average for the production of 1 tonne of aluminium foil. This oil consumption is significantly reduced compared to 41 kg calculated in 1998 for the thin gauge foil. For extrusion, the die cleaning operation consumes caustic soda for aluminium leaching as well as sulphuric acid for neutralising the used leaching bath. Caustic soda (11.3 kg) is used by tonne of extrusion in 2005 while 15 and 29 kg were respectively calculated in

2002 and 1998. Sulphuric acid (6.9 kg) is used in 2005 while no data were collected in the past for this input.

In sheet and foil production, VOC (volatile organic compounds) and organic hydrocarbon emissions to air result from the vaporising and possible decomposition of the oil used in the various rolling processes. VOC emission is a big concern for foil production. The significant reduction of VOC emissions shows that foil producers are progressively equipped with gas extraction and treatment units. While 12 kg of VOC was measured in 1998 per tonne of thin gauge aluminium foil, only 2.22 kg of VOC are calculated in 2005 per tonne of foil. For sheet production, VOC emission is slightly reduced from 0.44 kg/tonne of sheet in 1998 to 0.38 kg in 2005. The other air emissions are mainly linked to the fuel combustion.

The fabrication of sheet, foil and extrusion generates on average respectively 12.2, 30.5 and 38.1 kg of hazardous waste and 7.9, 16.3 and 15 kg of non-hazardous waste per tonne of semi-finished product. About 20% of these wastes are going to landfilling while the rest is further processed or incinerated. In comparison to past figures, the amount of waste which is landfilled is significantly down. Data related to waste for further processing were not collected in previous surveys so that a global comparison makes no real sense. As already mentioned, qualitative information should be collected in the future about the type of waste and the type of waste processing in order to include such operations in future LCI models. Only incineration with energy recovery has been included in the 2005 models.

#### 6.2.2 LCI data for semi-production processes

Table 20 reports LCI data regarding the consumption of fossil-based energy resources as well as the main air emissions for 1 tonne of semi-finished products. Detailed LCI data as well as environmental indicators for a pre-set of impact categories are available on request at [lcii@eaa.be](mailto:lcii@eaa.be). Figures reported in Table 20 are mainly linked to the thermal energy use and the electricity consumption. As a result, the consumptions of fossil-based energy resources reflect the trends which are observed for the end-use energy, as reported in Table 19: extrusion consumes slightly more than sheet and consumption for foil is about double in comparison to sheet. The same trends are observed for the main air emissions, i.e. CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>2</sub> and dust.

*Sensitivity to electricity grid mix* Electricity production is a major contributor to the above data since it contributes for about 2/3 for the consumption of the fossil-based energy resources and for the listed air emissions. In other words, this means that the electricity background data have a big influence on final LCI results. As highlighted in Table 6,

**Table 20** LCI data related to the consumption of fossil-based energy resources and the main air emissions for the production of 1 tonne of semi-finished products from an aluminium ingot

Type of semi-product		Sheet <sup>a</sup>			Foil			Extrusion		
Year	Unit	2005	2002 <sup>b</sup>	1998 <sup>b</sup>	Thin 2005	Thick 1998 <sup>b</sup>	1998 <sup>b</sup>	2005	2002 <sup>b</sup>	1998 <sup>b</sup>
Aluminium ingot input	kg	1,004	1,012	1,012	1,007	1,027	1,032	1,008	1,013	1,013
Fossil-based resources										
Crude oil	kg	26.5	21.4	21	62.7	79	58	22.7	31	43
Hard coal (crude)	kg	61.0	64.2	71.9	136.8	221	183	77.1	104	151
Brown coal (crude)	kg	97.6	67.7	75.7	216.2	233	193	126.2	110	158
Natural gas (crude)	kg	102.0	92.3	99.3	211.9	220	175	123.7	106	135
Main air emissions (kg)										
CO <sub>2</sub>	kg	589	464	499	1,238	1,367	1,090	683	632	860
NO <sub>x</sub>	kg	1.03	0.76	0.81	2.1	2.4	1.9	1.56	1.1	1.5
SO <sub>2</sub>	kg	2.11	1.52		5.9	4.8	3.9	2.6	3.2	3.2
Dust	kg	0.12	0.3	0.33	0.5	0.69	1	0.11	0.47	0.69

<sup>a</sup> Ingot homogenisation not included in 1998 and 2002<sup>b</sup> Dross recycling not included in 1998 and 2002

the 2005 model uses EU-25 LCI data for electricity while the UCPTE model was used in the past. The energy carriers and the associated air emissions are quite different for both models so that the contribution of electricity data in both models is quite different and is in general detrimental to the new LCI data, especially for the consumption of brown coal and natural gas and for the CO<sub>2</sub> emission. As a result, direct comparison with previous years' results does not reflect significantly the evolution of the foreground data. As example, the significant energy savings observed for extrusion and foil production are not fully reflected in the LCI data reported in Table 20. The use of the UCPTE model instead of the EU-25 model in 2005 would give about 75, 165 and 90 kg less CO<sub>2</sub> emissions respectively for sheet, foil and extrusion. In the future, a sensitivity analysis will be performed for better highlighting this issue.

### 6.3 Aluminium recycling

#### 6.3.1 Process data consolidation and averaging

Two datasets related to aluminium recycling have been developed in relation to the 2005 EAA environmental survey. The remelting dataset address the recycling of process scrap which is typically organised through the remelters and the refining dataset addresses the recycling of old aluminium scrap which is typically organised through the refiners.

**Furnace technologies** Two main furnace technologies are used to melt aluminium scrap: the reverbatory furnace and

the rotary furnace (Schmitz 2006). Reverbatory furnaces are more adapted for clean scrap while rotary furnaces are suited for lower quality scrap input. Remelters use mainly reverbatory furnaces so that the remelting model is based on this furnace technology only. Refiners use a combination of rotary and reverbatory furnaces. As a result, the 'refining' model is based on a mix of rotary (64%) and reverbatory furnace (36%) technologies.

**Treatment of by-products: dross recycling and salt slag processing** In absence of fluxing salt, melting aluminium usually produces residues, usually called dross, which is mainly composed of aluminium oxides and entrapped aluminium metal. Depending on the scrap input quality and size, between 20 and 100 kg of dross are produced per tonne of ingot with a metal content varying from 30% to 60%. Aluminium metal contained in dross is recycled as part of the aluminium refiners' operations. After cooling, large pieces of metal are separated from dross by manual sorting before feeding it to impact or ball mills in which the more friable aluminium oxide is ground up; metal fractions may then be recovered with subsequent screening operations. Aluminium metallics, as a product of dross recycling operations, are recovered by a variety of methods with varying yield. Dross can also be fed directly into rotary furnaces and treated with more or less salt flux. Specific data have been collected to model dross recycling.

Salt flux is used mainly in rotary furnace in order to clean the melt and to collect the contaminants within the so-called salt slag. Salt slag contains between 5% and 20% of aluminium metal. Most of the salt slag is treated to recover the aluminium metal. This treatment includes a crushing

and grinding process aiming at recovering the metal granulates which contain about 80% of aluminium metal. About 75% of the metal is recovered in the metal granulate. This metal granulates are melted in rotary furnaces. The non-metallic residue is then leached and the residual metal is oxidised. The oxides and others insoluble compounds are then separated from the leaching solution through filtration. The last step consists in a crystallisation process to regenerate the salt flux. Specific input and output data have been collected in order to model this salt slag treatment and associated aluminium and salt recovery.

**Scrap mass flow analysis for refining model** In order to model correctly aluminium recycling and to define the generic recycling route for the refiners, the aluminium scrap mass flow has been modelled according to the ESSUM methodology (Boin and Bertram, 2005). This scrap mass flow modelling has been done through a joint effort between the European Aluminium Association and the Organisation of European Aluminium Refiners and Remelters (OEA). The European consolidation of the scrap mass flow for the refiners is reported in Table 21. All figures are expressed in kilotonnes (kt). This model excludes the new scrap arising from aluminium product manufacturing which are partly recycled by the refiners. According to this model, 2,719 kt of scrap input as metal enters the European refiners, 64% of these scrap being melted in rotary furnaces and 36% in reverbatory furnaces. This furnace mix is used in the refining model. The typical European scrap mix used for this refining model is reported in the last column of Table 21. Turnings and foundry scrap represent respectively 25% and 7% of the input. Old scrap represents in total 68% of the input, almost 30% coming from transport, 16.5% from old packaging, 10.6% from engineering and 6.7% from consumer durables. Building scrap represent only 3.4% due to the long life span of the aluminium building products and the recycling route which is mainly organised through remelters.

**Scrap preparation for refining model** The scrap preparation is highly dependent on the scrap type and origins. A motor block engine, a used beverage can or a facade panel are not prepared in the same way before melting. Table 22 reports main scrap preparation processes which are applied to the various scrap categories. While some preparation processes are applied systematically to the whole scrap flow, other processes are only applied to a fraction of the scrap flow. It is particularly the case for shredding (including eddy current separation), sink and float, cutting and balling. The estimated percentage of scrap flow entering these processes is mentioned in bracket.

Based on Tables 21 and 22, the percentages of the European scrap mix entering the various preparation

**Table 21** Scrap mass flow for the aluminium refining model (see EN 12258-3 for definition of scrap type)

Scrap input (as metal)	Rotary furnace	Reverbatory furnace	Total	
Unit	kt	kt	kt	
Foundry scrap	190	0	190	7.0%
Turnings	346	346	691	25.4%
Cans and rigid packaging (old)	11	217	228	8.4%
Flexible packaging (old)	71	150	222	8.1%
Building (old)	0	94	94	3.4%
Shredded transport scrap (old)	642	0	642	23.6%
Dismantled transport scrap (old)	15	139	154	5.7%
Engineering (old)	260	29	289	10.6%
Consumer durables (old)	183	0	183	6.7%
Other (old)	28	0	28	1.0%
Total	1,745	974	2,719	100.0%
Scrap input share	64%	36%		

processes have been estimated and are reported in Table 23. These percentages have been used to model the scrap preparation phase. Except for de-lacquering and wrought aluminium shredding, it has not been possible to collect updated input and output figures for unit processes of the scrap preparation phase. As a result, unit processes data related to the previous survey have been used to produce the new consolidated model for the scrap preparation. This is deemed as an acceptable representation of the 2005 situation, as no major changes were recorded in scrap preparation practices since 1998. These scrap preparation unit processes data were eventually combined with the actual scrap mass flow fractions as reported in Table 23.

**Direct inputs and outputs** Table 24 reports the average direct inputs and outputs for process scrap remelting on one side and for old scrap refining on the other side for the production of 1 tonne of aluminium ingot. Data for remelting do not include dross recycling while such dross recycling and salt slag treatment are included in the refining data.

In 2005, remelters used 1,009 kg of clean aluminium scrap (70%) and ingot for remelting (30%) as well as 29 kg of alloying elements for producing 1 tonne of ingot. In theory, remelters could melt aluminium scrap without any addition of alloying elements. However, in practice, remelters usually do not use aluminium input exclusively composed of scrap. Ingots for remelting and alloying elements are also used in order to adjust the

**Table 22** Main scrap preparation processes according to scrap type

Scrap mass flow	Main preparation processes
Foundry scrap	No processing
Turnings	Drying and de-oiling
Cans and rigid packaging (old)	De-lacquering and baling
Flexible packaging (old)	Baling
Building (old)	Shredding (50%), sink and float (20%), balling and cutting (20%)
Transport (old)	Shredding (80%), dismantling (20%), Sink and float (40%)
Engineering (old)	Shredding (100%), sink and float (40%)
Consumer durables (old)	Shredding (100%), sink and float (40%)
Other (old)	Shredding (100%), sink and float (40%)

alloy composition of the aluminium ingot. This quantity of alloying elements does not play any role in the LCI model since it is substituted by aluminium, i.e. aluminium scrap in the remelting model. No significant changes are observed regarding metal input of the remelting in 2005 in comparison to 2002 and 1998. For the refining process, the scrap input is higher due to the presence of contaminants and the addition of alloying elements is also much more significant since refiners produce usually cast aluminium alloys which require more alloying elements than wrought aluminium alloys. In addition to the aluminium ingot, the remelting process produces 42 kg of dross which contains about 25 kg of aluminium metal (60%). This dross is recycled within the remelting model. For the refining process, the main aluminium by-product is the non-metallic residue of the salt slag treatment, i.e. mainly aluminium oxide, which represents 107 kg in 2005.

Remelters and refiners use mainly natural gas as energy source, respectively 68 and 84 kg per tonne of aluminium ingot. Small quantities of heavy oil and propane are also consumed by the remelters while refiners use about 4 kg of diesel per tonne of aluminium ingot. Since 1998, the thermal energy consumption of the remelters appears quite stable or slightly up around 3,200–3,400 MJ by tonne of aluminium ingot. The electricity consumption of the remelters is relatively small, i.e. 133 kWh per tonne. In 2005, the refining of old scrap consumes 3,990 MJ of thermal energy from fuels, i.e. 20% more than for remelting. For the refining, it is estimated that 10 to 20% of additional thermal energy comes from the combustion of contaminants (mainly polymers). Within the refining model, it has been assumed that an additional thermal energy of 600 MJ, i.e. representing about 15% of the thermal energy supplied by the fuels, comes from the combustion of 25 kg of polyethylene contaminating the

aluminium scrap. Compared to 1998, the thermal energy use as well as the electricity consumption is significantly reduced in 2005. This spectacular reduction results from three main reasons:

- In 1998, figures related to energy use by refiners were probably overestimated
- In 2005, furnace technologies used by European refiners are significantly improved especially in terms of energy transfer and burners technology
- Induction furnace is not considered in 2005 consolidation so that electricity use is also significantly diminished.

Remelters use very small quantity of fluxing salt. Fluxing salt is mainly used by the refiners within the rotary furnace. A salt consumption of 11.3 kg is calculated considering the salt which is recovered from the salt slag treatment. In practice, the salt input in the rotary furnace is much higher, i.e. between 200 and 300 kg by tonne of metal input.

Slightly more than 2 kg of argon per tonne of aluminium ingot is used by the remelters as protective gas. Refiners use less argon than remelters, about 1 kg per tonne of aluminium ingot, but they consume also nitrogen gas, about 3 kg per tonne. A small quantity of chlorine is used by the remelters and the refiners for the melt treatment.

Water is mainly used for cooling. For the remelting process, 9.7 m<sup>3</sup> of water input is measured by tonne of ingot in 2005 while 78 m<sup>3</sup> was calculated in 1998. Water input for the remelting is then significantly reduced. Water input for the refining is about double, 17.8 m<sup>3</sup> are measured. Water output reaches respectively 9.2 and 8.8 m<sup>3</sup>, giving a respective consumption of 0.5 m<sup>3</sup> for the remelting and 9 m<sup>3</sup> for the refining by tonne of aluminium ingot.

For remelters, air emissions are mainly linked to the fuels combustion. NO<sub>x</sub> is the main detrimental emission. About 50 g of SO<sub>2</sub> is emitted by tonne of ingot due to the use of small quantities of heavy fuels. Fifty grams of VOC

**Table 23** Scrap mass flow fraction entering the various scrap preparation processes

Preparation process	Scrap mass flow fraction	Input and output data
Shredding—wrought alloys	25.0%	Year 2005
Shredding—cast alloys	30.0%	Year 1998
Sink and float	15.0%	Year 1998
Cutting and baling	20.0%	Year 1998
Drying and de-oiling	25.0%	Year 1998
De-lacquering	10.0%	Year 2005
Dismantling	5.0%	No data
No pre-treatment	10.0%	

**Table 24** Direct input and output data for the production of 1 tonne of aluminium ingot by the two recycling routes: remelting and refining

Year	Unit	Process scrap remelting and casting (excluding dross recycling)			Old scrap refining and casting (including dross recycling and salt slag processing)	
		2005	2002	1998	2005	1998
Metal inputs						
Old scrap (metal+contaminants)					1,054	1,033
Clean process scrap and ingot for remelting	kg	1,009	1,014	1,014		
Alloying elements	kg	29	25	21.8	64	78
Main aluminium outputs						
Aluminium ingot	kg	1,000	1,000	1,000	1,000	1,000
Dross/skimmings (for recycling)	kg	42	42	32.7		
Metal content of dross/skimmings		60%	60%	60%		
Aluminium oxide (residue)					107	119
Energy inputs						
Heavy oil	kg	2.7	5.6	1.7		
Diesel and light fuel oil	kg	0.3	0.3	0.1	4.00	17.1
Natural gas	kg	68.1	67.2	67.0	83.7	202.8
Propane	kg	2.7		0.0		
Total thermal energy	MJ	3,367	3,314	3,136	3,990	9,971
Electricity	kWh	133	179	174	61	354
Ancillary products, inputs						
Fluxing salts	kg	0.50	0.68	0.89	11.3	13.7
Argon	kg	2.26	1.56	2.67	0.97	
Nitrogen (N <sub>2</sub> )	kg				3.20	1.8
Chlorine	kg	0.14	0.14	0.039	0.25	1.6
Water	m <sup>3</sup>	9.66	12.55	78	17.8	N.L.
Emissions to air						
Chlorine	kg	0.006			0.002	0.0005
Carbon monoxide (CO)	kg	0.095				
Dust/particulates, total	kg	0.041			0.021	0.03
NO <sub>x</sub> , as nitrogen dioxide	kg	0.329				
SO <sub>2</sub>	kg	0.051				
VOC	kg	0.050				
Water output						
Water output	m <sup>3</sup>	9.17			8.8	
Waste (excluding dross, aluminium scrap and demolition waste)						
Hazardous waste for landfilling (including filter dust)	kg	2.69			18.24	26.1
Hazardous waste for incineration	kg	0.06				
Total hazardous waste	kg	2.75	2.70		18.24	26.10
Non-hazardous waste for landfilling	kg	0.32				
Non-hazardous waste for incineration	kg	0.27				
Non-hazardous waste for further processing	kg	1.01			1.20	2.2
Total non-hazardous waste	kg	1.59	6.00	1.5	1.20	2.20

by tonne of ingot comes from the oil which contaminates the process scrap. Air emission data collected among the refiners are relatively weak and do not allow reporting robust European averages.

Solid waste production is quite limited for the remelting process. For refining, most of the hazardous waste is composed of the filter dust which is usually landfilled.

### 6.3.2 Material flow and LCI data for remelting and refining

While the material flow for the remelting model is quite simple, the refining model appears quite more complicated considering the scrap preparation phase, the two furnace technologies as well as the dross recycling and the salt slag processing. Figure 7 reports the material flow diagram which has been used for the refining model.

Table 25 reports the main LCI data calculated according to the two models, i.e. the main solid materials flows, the fossil-based energy resources and the main air emissions.

Regarding the aluminium mass flow, the remelting model calculates 1,007 kg of scrap input as metal, i.e. a

metal loss of 7 kg for the production of 1 tonne of ingot. Comparison with 1998 and 2002 is not possible since dross recycling was not included and the scrap input does not refer to metal only. The total metal input considering the alloying elements reached respectively 1,039 and 1,036 kg in 1998 and 2002. It is likely that such quantities are slightly overestimated considering the scrap contamination. In 2005, the only significant aluminium output of the remelting model is the aluminium ingot while aluminium dross is also part of the output in 2002 in 1998, respectively with 42 and 33 kg.

For the refining model, it is estimated that 1,319 kg of raw scrap enters the scrap preparation phase. This raw scrap input is composed of 1,108 kg of metal and 211 kg of contaminants. Also, 1,055 kg of scrap as metal exits the scrap preparation and enters the refining process, 675 kg being melted in rotary furnaces and 380 kg in reverberatory furnaces. Three main sources contribute to the production of 1,000 kg of aluminium ingot: 346 kg comes from the reverberatory furnace, 601 kg from the rotary furnace and 53 kg from the dross recycling and salt slag processing. In addition to the aluminium ingot, 330 kg of solid output is

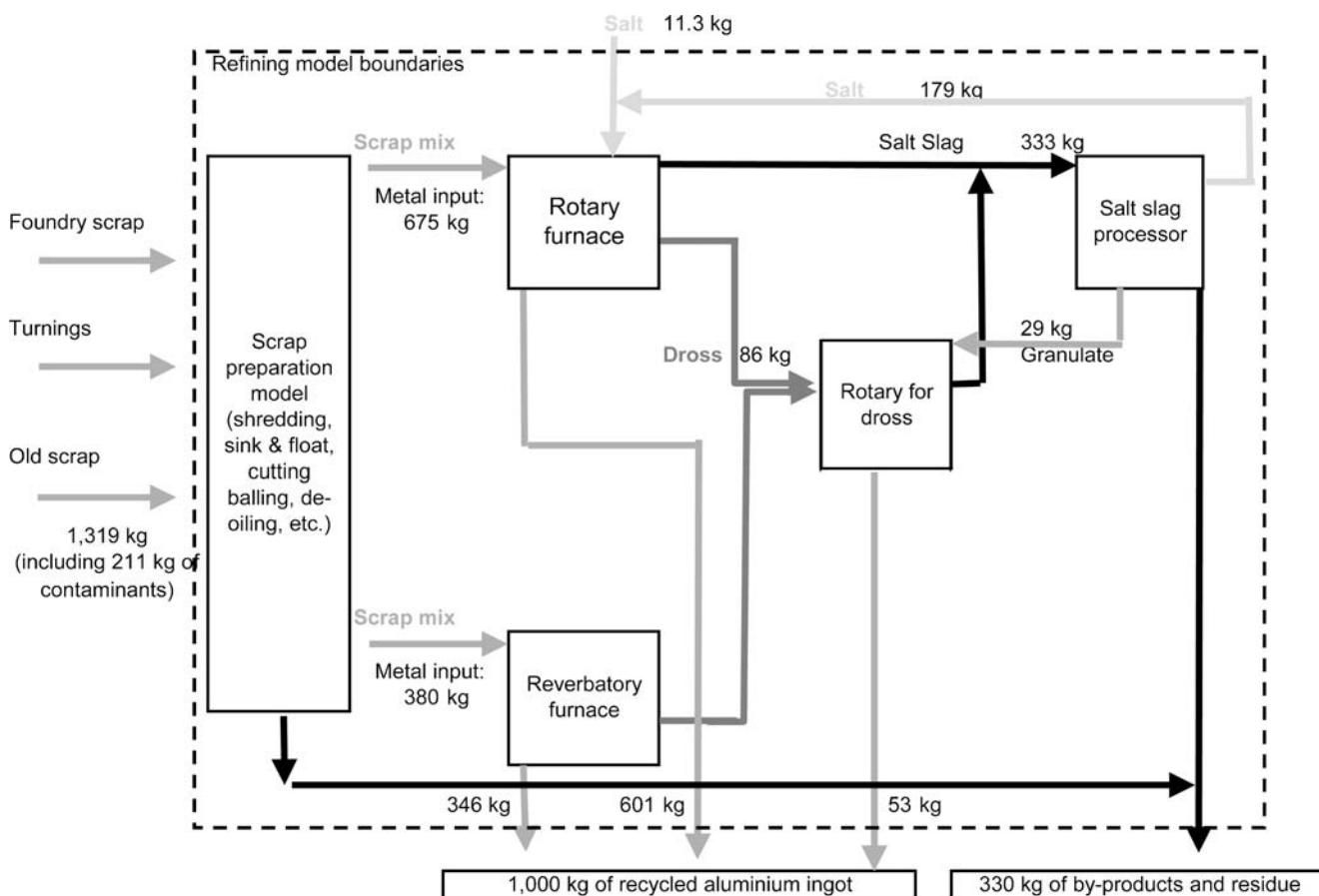


Fig. 7 Material flow diagram of the refining model

**Table 25** Main LCI data for the production of 1 tonne of aluminium ingot according to remelting and refining models

Year	Remelting			Refining	
	2005	2002	1998	2005	1998
Solid inputs (kg)					
Total scrap input (preparation phase)				1,319	1,270
Total metal input				1,108	
Foreign materials				211	
Scrap input melting	1,007 <sup>c</sup>	1,014	1,014	1,055 <sup>c</sup>	1,033
Alloying elements <sup>a</sup>		25	22		78
Solid outputs (kg)					
Aluminium ingot	1,000	1,000	1,000	1,000	1,000
Dross <sup>b</sup>	0	42	33		
Aluminium oxide (from salt slag processing)				107	119
Iron scrap (mainly from preparation phase)	0.5			38	12
Residues and waste from preparation phase (rubber, filter dust, etc.)	9.8	7	1.5	180	162
Fossil-based energy resources (kg)					
Crude oil	5.9	11.9	6.2	10.9	32.3
Hard coal (crude)	12.5	20.0	18.7	15.3	45.8
Brown coal (crude)	20.1	21.5	20.1	23.2	49.6
Natural gas (crude)	87.5	74.0	76.7	120.1	233
Main air emissions (kg)					
CO <sub>2</sub>	298	291	316	481	801
NO <sub>x</sub>	0.39	0.42	0.41	0.55	1.1
SO <sub>2</sub>	0.52	0.81	0.53	0.7	2
Dust	0.06	0.12	0.1	0.17	0.29
Organic emissions	0.84	0.89	0.96	1.08	2.6
VOC (unspecified)	0.05				
Methane	0.72			0.97	

<sup>a</sup> Substitution of alloying elements in 2005 model

<sup>b</sup> Dross recycling not included for the remelting model of the years 1998 and 2002

<sup>c</sup> As metal only

calculated. The scrap preparation generates 38 kg of iron scrap and 180 kg of residue and waste while the main solid output from the refining process is 107 kg of non-metallic residue from the salt slag processing which is mainly composed of aluminium oxide.

Crude natural gas is the major source of fossil-based energy resources for both models. According to these models, scrap remelting consumes 87.5 kg while aluminium refining consumes 120.1 kg of crude natural gas by tonne of aluminium ingot produced. Coal consumption is mainly linked to the electricity production. While these consumptions of fossil-based energy resources are quite stable over years for remelting, the refining model shows a strong decrease of these consumptions due to the much lower consumption of fuels and electricity. It can be estimated that the combustion of fossil-based energy resources have been reduced by about 50% in comparison to the year 1998.

The main air emissions follow the same trend as the consumption of fossil-based energy. For remelting, CO<sub>2</sub> emission is quite stable around 300 kg over the years while a strong decrease from 801 kg down to 481 kg is calculated for refining between 1998 and 2005. The other air emissions are stable over years for remelting while a significant decrease is observed for refining.

### 6.3.3 LCA and aluminium recycling

Preserving the aluminium metal during the whole product life cycle and during recycling should be a main goal for aluminium products since recycled aluminium can be used for producing new wrought or cast aluminium alloys which are used for new products. As a result, any LCA study needs to consider and to credit properly the ability of aluminium to be recycled, usually without any down-grading properties. The European aluminium industry

recommends using the so-called substitution methodology which considers that recycled aluminium substitutes primary aluminium so that only metal losses during the whole life cycle needs to be balanced by primary aluminium. Details about such methodology are given in the technical document ‘LCA and aluminium recycling’, which can be downloaded from the EAA website ([www.aluminium.org](http://www.aluminium.org)).

As a result, it is crucial to evaluate correctly the metal losses arising during the recycling phase. The ‘refining model’ reported in this document is only valid for the scrap mix reported in Table 21. The actual mix of recycling techniques applied to a specific product depends on many factors. The treatment of recycling in each specific LCA study should preferably be discussed with aluminium industry representatives. Table 26 reports specific estimates of metal losses for various old scrap categories (Boin and Bertram, 2005). It is recommended to use such specific metal losses within LCA studies. These metal losses refer to the scrap melting and refining phase. Possible losses associated with the collection of the end-of-life aluminium products and the scrap preparation are not included.

Within the European Reference Life Cycle Data System (ELCD 2006), two generic LCI datasets have been developed from a ‘cradle to recycling’ perspective, respectively for 1 kg of aluminium sheet and for 1 kg of aluminium profile. These two datasets related to aluminium semi-finished products have been developed on basis of the EAA LCI datasets on the production and transformation processes described in this report. These datasets include the aluminium ingot production and the fabrication of the semi-finished products. The two LCI datasets and the documentation can be downloaded from the

website of the European platform on LCA (<http://lca.jrc.ec.europa.eu>)

## 7 Conclusions, recommendations and perspectives

This paper highlights the methodology used by the European aluminium association for developing robust generic LCI datasets on aluminium production and transformation processes, in accordance with ISO standards as confirmed by the critical reviewing. The publishing of these LCI datasets shows the commitment of the European aluminium industry to contribute in a transparent, fair and scientifically sound manner to product sustainability in a life cycle thinking perspective.

Even if the quality and the completeness of these LCI data reach a very high standard, some areas for data improvements have been identified. Land use, water use and solid waste treatment appear as three priority areas for data refining and improvement. The land use dimension, particularly meaningful for bauxite mining, is not covered in the current LCI data while it is now integrated within many LCA studies. Up to now, the reporting of meaningful and robust data on water origins and use have not been possible due to the huge discrepancies between the surveyed sites combined with the difficulty to report coherent input and output water mass flows. The development of water data, only focussing on water-stressed areas, will most probably make more sense in the future. Finally, collecting more qualitative information about solid waste processing and treatment will help to include such operations within the system boundaries and to model their associated air, water and soil emissions.

Software houses and LCA practitioners are invited to update their generic European data on aluminium with these new LCI datasets. The EAA environmental report (EAA 2008) is available for download on the EAA website while the full LCI datasets are available on request at [lci@eaa.be](mailto:lci@eaa.be).

**Table 26** Metal losses at the refining process for various old scrap categories (Boin and Bertram, 2005)

Old scrap types	Estimated metal losses for the melting process
Building	1–4%
Shredded transport scrap	4–8%
Dismantled transport scrap	2–4%
Used beverage cans	2–3%
Mixed packaging and foil	2–8%
Engineering	3–7%
Consumer durables	3–7%
Total old scrap	4–6%
Total refining model	5%

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